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ENGINEERING MATERIALS

BY

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"AUTOMOBILE AND TRUCK ENGINE" "AUTOMOBILE
ELECTRICAL MAINTENANCE" "AUTOMOBILE ENGINE OVERHAUL," ETC.

VOLUME I

THE FERROUS METALS

SECOND EDITION



LONDON

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PREFACE

The present volume is a completely revised and largely rewritten version of the last edition of a work that was published originally in 1920, and has since had a good reception by engineers and others concerned with the selection and application of metals. It forms the first volume of a series of three, of which the second volume deals with the non-ferrous metals and their alloys, plastic and other organic materials, the third volume is devoted to the theory and testing of engineering materials.

This volume is intended primarily, for the engineer, designer, instructor, and other users of steels and irons, it deals with the most important of the available metals, their mechanical and physical properties, composition, heat treatments, and commercial applications. It should, therefore, form a useful guide and reference work to the selection of the most suitable metals for any desired purposes.

In the preparation of this book the needs of the aircraft and automobile engineer were accorded first attention, but in addition it was decided to include the major requirements of the mechanical and constructional, chemical and electrical engineer.

Since the last edition was published there has been a considerable amount of research and development work, notably in connection with alloy steels and cast irons, so that to-day there is available a relatively large number of new metals, each with its own particular applications, e.g. wear resistance, heat or corrosion resistance, maximum hardness, toughness, ductility, tensile strength, fatigue resistance, etc.

It should be mentioned that no attempt has been made to give anything but a bare outline of the metallurgical or metallographical aspects of the subject, and this has been included only in order to give the reader an elementary knowledge of the constituents of steels and irons and of the thermal effects on the nature and arrangements of these constituents.

In order to extend the field of usefulness, the present volume includes information relating to the machining of steels and irons, ferrous, brazing and welding, and certain other practical aspects.

In regard to the scope of this book, whilst intended to cover the needs of the manufacturer, engineer, and designer, it should also be useful to the draughtsman and student, the range of its contents can best be judged by a survey of the index at the end.

In conclusion, the writer would like to record his appreciation of assistance given in the preparation of this volume by various institutions, and individuals; in particular to Messrs. T. Firth J. Brown, Ltd.; Edgar Allen, Ltd.; the Bureau of Information; Nickel; the Copper Development Association; the Institution of Automobile Engineers; the Institution of Mechanical Engineers; the Royal Aeronautical Society, and to Dr. W. H. Hatfield.

A W JUDG

FARNHAM, SURREY
1943

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ENGINEERING MATERIALS

CHAPTER I

THE FERROUS METALS

Iron—Historical

THIS important metal, which forms the principal constituent of all modern irons and steels, has been known to mankind for over 2000 years, the earliest evidence of its existence being that of the Early Iron Age (1000-500 B.C.), for iron tools of this epoch have been found at Hallstatt in Austria. Mention of the manufacture of steel was also made by Aristotle (384-322 B.C.).

Apart from the existence of meteoric iron, which must have been known to the ancients, perhaps the most striking example of the use of iron in early times is that of the Delhi Iron Pillar, believed to date back to A.D. 300. This remarkable column stands 24 ft. in height, weighs about $6\frac{1}{2}$ tons, and consists of nearly pure iron, so that it was evidently produced by a forging process. Sir Robert Hadfield* has given the percentage analysis of a sample of iron from this pillar, to indicate its comparative purity as judged even by modern standards; it was as follows: Iron, 99.720; carbon, 0.080; silicon, 0.046; sulphur, 0.006; phosphorus, 0.114; manganese, nil. The specific gravity was 7.81 and the Brinell hardness 188.

The early method of producing iron from its ores—which exist on the surface or at shallow depths—was to use a furnace about 3 ft. high and 1 ft. diameter, having air holes below. The furnace was heated with charcoal and when thoroughly hot was charged with iron ore and charcoal, usually arranged in alternating layers. The crude iron thus produced was afterwards refined by heating to redness and hammering, the process being repeated until most of the slag, earth, and other inclusions had been removed; the product thus obtained was a kind of wrought iron. It is probable that both cast iron and steel were also discovered in ancient times, for the method of reducing the iron ore with charcoal would, if the proportions were varied, result

* *Sinhalese Iron and Steel of Ancient Origin*, Sir R. Hadfield, *Proc. Roy. Soc.*, 1912.

in a metal containing different proportions of carbon. Thus, it is known that in some of the early attempts (A.D. 1-600) to extract the iron, skin bellows were used, so that higher smelting temperatures were obtained; with an excess of charcoal the brittle form of iron, containing from 2 to 5 per cent of carbon, might conceivably have been produced.

Similarly, steel—which became more widely known during the period A.D. 600-1000—was no doubt produced by accident, for the inclusion of carbon from the charcoal, in small amounts, namely, up to about 1 per cent, in the metal, which was afterwards subjected to repeated heating and hammering, would result in the production of a steel of some kind. It is also very probable that the hardening property of steel was discovered accidentally, when the heated metal was cooled by quenching it in water.

Production of Iron

Modern irons and steels contain from about 94 to 99.9 per cent of pure iron, the latter metal being obtained from iron ores by smelting and subsequent refining processes.

The commonest type of iron produced commercially is pig or cast iron. As the process of obtaining this form of iron is a comparatively simple one, a brief outline of the method employed will be given.

The iron ores generally used for making cast irons in the blast furnace include Magnetite (Fe_3O_4), Haematite (Fe_2O_3), Limonite ($2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$), Siderite or Spathic iron ore (FeCO_3), and Pyrites (FeS_2). The former contains about 72 per cent of iron, and the others smaller percentages down to 46.7 per cent in the case of pyrites.

It is necessary to purify the ore used for commercial iron making before it can be used: the usual process adopted necessitates the deoxidation of the ore, followed by its separation from the other associated mineral matter, e.g. clay, quartz, etc.

The iron ore is melted in a furnace, known as a blast furnace, in contact with other carbon-bearing materials, such as coke, charcoal, or anthracite, so that the oxides in the ore are converted into carbon monoxide (CO) or carbon dioxide (CO_2); the result is that all of the oxygen is removed from the ore. During the iron ore smelting process the impurities formed, consisting of silica in combination with earths and metallic oxides, known as *slag*, float on the surface of the molten iron, and are removed by tapping the furnace at a little higher level than that of the iron. During the smelting process the iron that has been deoxidized becomes nearly saturated with carbon, taking up from 3.5 to 4 per cent. This absorption of carbon (termed carburizing)

is an important part of the iron-smelting process, for through it alone can the iron be made fusible enough to melt at the temperatures that can be generated in the blast furnace; it is only when the iron is liquid that it can be properly separated from the slag. Further, the iron is heated so far above its melting-point that it can be run out through the tapping holes of the furnace whilst still molten into the casting moulds, situated at appreciable distances from the furnace, and even carried in clay-lined ladles to other furnaces where it is to be converted into steel.

Fig. 1 illustrates, diagrammatically, a typical blast furnace, and demonstrates the method of extracting the iron from its ores. The blast furnace is usually from 80 ft. to 100 ft. or more in height, and about 18 ft. to 20 ft. wide at its maximum cross-section. The lumps of iron ore, fuel, and limestone are charged through the hopper from the ore bucket *G* at the top, and, as shown, the interior of the blast furnace is filled to a level just below the throat. The ore is deoxidized during its descent, and eventually reaches the carburizing zone near the base, and finally the molten iron tapping hole *N*, that is normally stopped with clay. The slag is drawn off a little higher through the hole, or "cinder notch," *P*.

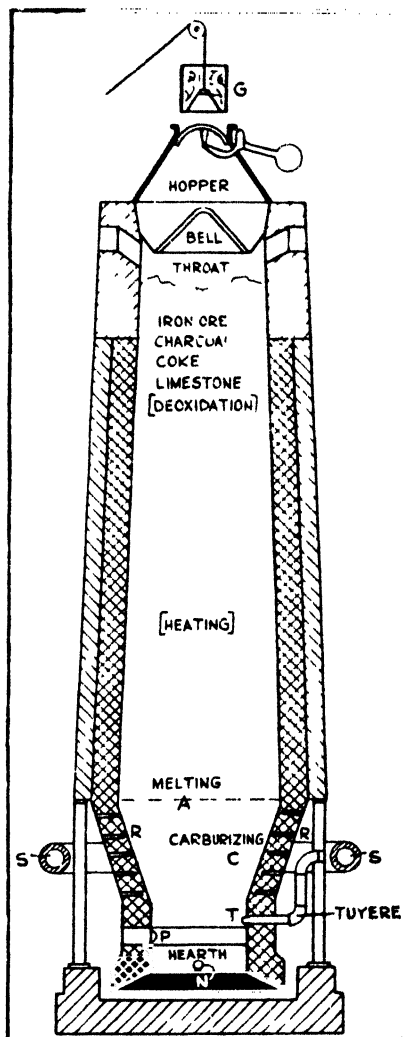


FIG. 1. ILLUSTRATING A TYPICAL BLAST FURNACE

The slag is drawn off a little higher through the hole, or "cinder notch," *P*.

Heated air under pressure is forced through nozzles or "tuyeres" *T* near the bottom of the furnace, to supply oxygen for burning the coke or fuel introduced with the ore. It is the heat thus generated that melts the iron deoxidized above, and also the other minerals of the ore, termed the "gangue," which unite with the lime of the limestone and the ash of the fuel to form the slag previously referred to.

Referring again to Fig. 1, *S* denotes the air supply or "blast" pipe, *A* the melting or fusion level of the furnace, and *R* the water-cooled boxes around the hottest portions, or "boshes."

The molten iron thus obtained is afterwards tapped from the furnace and directed into sand moulds of suitable form, where it afterwards solidifies into rectangular bars or "pigs." It is from the latter that the various grades of cast and wrought irons and finally the steels are ultimately produced by different refining processes.

Wrought Iron

This hitherto important metal, consisting of at least 99 per cent iron, is now seldom employed for commercial purposes on account of its inferior physical properties as compared with those of the low-carbon steels. In its purified form, however, it has important applications in the electrical industry.

Wrought iron is obtained from cast iron by the process of puddling, forging, and rolling, after which treatment only a very small percentage of carbon remains, usually from 0.05 to 0.15 per cent.

Certain impurities, such as manganese, silicon, sulphur, and phosphorus, are usually found in the resulting metal, and its physical properties are affected thereby. For example, the effect of more than about 0.1 per cent of phosphorus in iron is to make the metal *cold short*, i.e. to cause it to crack if bent cold, although it may be readily bent hot.

Sulphur, if present to a greater extent than about 0.1 per cent, causes *red shortness*, i.e. a tendency to fracture during hot forging or working.

Wrought iron is a silvery metal having a fibrous structure in the rolled or forged condition due to the presence of small quantities of slag in the original ingots. It is for this reason that wrought-iron bars and plates show different mechanical properties along and across the direction of rolling. The presence of these slag particles can be detected by microscopical examination.

There are different grades of wrought iron, ranging from the ordinary merchant bar to the treble best and charcoal irons. The

latter, which include the Swedish irons, are the purest grades, and are used for electrical parts, such as armature stampings, transformer cores, magnet keepers, etc.

Properties of Wrought Iron

(Wrought iron cannot be hardened by heating to a temperature just above the upper critical temperature, or "arrest" point ($860^{\circ}\text{C}.$), and quenching in water, although slight changes in the mechanical properties can be produced by quenching and reheating at different temperatures below the stated value.

Wrought iron has a specific gravity of 7.8 to 7.9, according to the grade.

A cubic foot of iron of 7.78 specific gravity weighs 486 lb.; a cubic inch weighs 0.281 lb.

The coefficient of linear expansion is 10.2×10^{-6} .

The thermal conductivity* is 0.144 (C.G.S. units) at $18^{\circ}\text{C}.$ and 0.143 at $100^{\circ}\text{C}.$

For pure iron the corresponding values at $18^{\circ}\text{C}.$ and $100^{\circ}\text{C}.$ are 0.161 and 0.151 respectively.

The specific heat, between $20^{\circ}\text{C}.$ and $100^{\circ}\text{C}.$, is 0.119,* and from $0^{\circ}\text{C}.$ to $1100^{\circ}\text{C}.$ 0.153.†

The electrical resistivity of pure and wrought iron at $18^{\circ}\text{C}.$ are 9 to 15×10^{-6} and 13.9×10^{-6} ohms per sq. cm. respectively.

Iron melts at $1530^{\circ}\text{C}.$, attains a cherry-red heat at $750^{\circ}\text{C}.$ to $780^{\circ}\text{C}.$, and a bright yellow heat (forging condition) at $850^{\circ}\text{C}.$ to $900^{\circ}\text{C}.$

In regard to the mechanical properties of wrought iron, tensile strength values lie between the limits of 16 and 25 tons per sq. in., according to the grade and condition. The tensile strength of the best wrought irons varies between 20 and 25 tons per sq. in. for flat sheet and strip metal, with an elongation of 20 to 25 per cent and reduction of area of 50 to 60 per cent; the values given refer to tests made on the metal in the direction of rolling.

When taken across the direction of the fibres the tensile strength ranges from about 15 to 22 tons per sq. in., but the reduction of area is usually greater, namely, from 70 to 80 per cent.

Wrought iron shows a well-marked yield point of from 15 to 17 tons per sq. in.; its elongation is about $\frac{1}{1000}$ of its length for each ton per sq. in. within the elastic limit, which varies from 14 to 16 tons per sq. in. for good qualities of this iron.

The compressive strength of wrought iron is rather indefinite, but may be taken at 25 to 30 tons per sq. in.

* Schmitz.

† Harker.

The shearing strength varies from 15 to 20 tons per sq. in., and is less when sheared along the direction of rolling (or parallel to the slag grain).

The modulus of elasticity for wrought iron varies from 12,000 to 13,000 tons per sq. in., being about 12,500 upon the average.

The modulus of rigidity is about 5000 tons per sq. in.

Best Yorkshire Wrought Iron

This widely used iron is made wholly from "puddled" pig iron, no scrap of any kind being used in the puddling furnace or in the piles. As specified in the British Standard Specification No. 858 (1939), the percentage chemical composition is as follows: Manganese, 0.06 (max.); phosphorus, 0.16 (max.); iron, the remainder.

Tensile tests upon round and square sections up to 4 in. should give values of 20 to 25 tons per sq. in.; minimum percentage elongations of 26 to 38; and minimum reductions of area of 39 to 52 per cent, according to the specified sizes and condition, i.e. whether rolled or machined. The minimum yield point should be from 50 to 56 per cent of the tensile strength. For plates of $\frac{1}{2}$ in. to 1 in. the tensile strengths with and across the grain should be 21 to 24 and 20 (min.) respectively.

Other tests specified include cold bend ones, nick and bend tests, forged-down tensile tests, welded bar tests and nick and fracture tests.

Wrought Iron for General Engineering Purposes

The wrought irons employed in this country for general engineering purposes are covered by the B.S.I. Specification No. 51 (1939), which includes three grades, namely, *A*, *B*, and *C*. The whole of the iron supplied to this Specification is of "puddled" wrought iron and the manganese content must not exceed 0.10 per cent.

The tensile tests upon standard specimens of round form are specified to give tensile strength values of 20 to 25 tons per sq. in., with elongations of 20 to 35 per cent and reductions of area of 38 to 50 per cent, according to the diameter or size of the specimen and its condition, i.e. whether as rolled or machined.

In the case of plates the tensile strengths with the grain must lie within 20 and 24 tons per sq. in., and across the grain from 17 to 21 tons per sq. in., with minimum elongations of 3 to 10 per cent, according to the thickness of the plate.

A number of other tests specified include cold bend ones, hot bend tests, nick and bend tests, welded bar tests, quench tests, and the "ramshorn" test.

The *quench test* consists in heating a specimen to a yellow heat

(1038° C. to 1093° C.) and suddenly quenching it in water below 90° F. It must withstand this test without showing cracks or flaws when bent through an angle of 180° round a former having a diameter equal to the diameter or thickness of the test piece, until the limits are parallel.

The *ramshorn test* is specified as follows: The test pieces shall be punched at a full red heat 1500° F. to 1600° F. (816° C. to 871° C.) with a punch one-third the diameter or width of the bar, at a distance

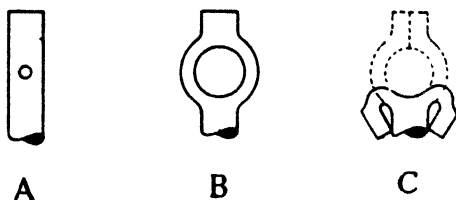


FIG. 2. THE RAMSHORN TEST FOR IRON

from the end of the bar equal to one and a half times the diameter or width (Fig. 2 (A)). While still hot the hole shall then be drifted out to one and a quarter times the diameter or width of the bar (Fig. 2 (B)). The end of the bar up to the hole shall then be split, and the ends shall be turned back without any extension of the original split or indications of fracture, cracks, or flaws (Fig. 2 (C)).

Electrolytic Iron

A much purer form of iron than the wrought variety is that known as electrolytic iron, which is produced from less pure irons, or from low-carbon steels (or even cast iron) by deposition in an electrolytic bath. The anode consists of the less pure iron-containing metal, whilst the pure iron cathode receives deposited pure iron. The electrolyte usually consists of a neutral solution of iron salts such as ferric chloride, ferric sulphate, etc. A typical solution which has been used for building up worn steel parts with iron consists of ferrous ammonium sulphate at a strength of 75 grams per litre of water. The current density employed in making electrolytic iron varies from 12 to 75 amperes per sq. ft.

The method used by the Le Fer Company of Grenoble* included the use of a revolving cathode and a neutral solution of iron salts kept in a neutral state by the circulation of the liquid over the surface of the iron. A depolarizing material, such as iron oxide, was added,

* *Electrolytic Iron*, L. Guillet, *Proc. Iron and Steel Inst.*, 1914.

periodically, to get rid of the hydrogen which formed on the cathode. It was thus found possible to work with a current of high density (1000 amperes per square metre), and an iron of excellent quality was obtained. The process is applicable to the direct manufacture of tubes and sheets in the finished state.

The average composition of electrolytic iron is approximately as follows: Carbon 0.004; silicon 0.007; sulphur 0.006, phosphorus 0.008; iron 99.975 (percentages).

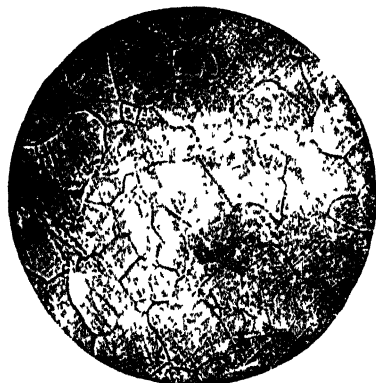


FIG. 3. ELECTROLYTIC IRON
(ANNEALED) Etched 300

Electrolytic iron in the deposited state is hard and brittle, showing under the microscope a characteristic grain resembling the fine needles of martensite.

Upon annealing from about 700 C. to 800 C. the well-known ferritic structure (Fig. 3) is obtained, the annealing process not only improves the strength qualities but also serves to eliminate the absorbed gases, such as the hydrogen and carbon monoxide.

The tensile strength of the annealed iron averages about 20 tons per sq. in. with an elonga-

tion of about 40 per cent in the direction of the length of the cathode.

Tubes and plates made of electrolytic iron show a remarkable degree of deformation before signs of fracture appear.

The Brinell hardness ranges from 193 for the deposited metal down to 90 for the metal in the annealed condition.

Electrolytic iron has been employed in electrical work where high magnetic permeability and low hysteresis are necessary, but it has now been replaced to a considerable extent by special alloys of high permeability.

The electrical conductivity of this iron (annealed) is 10.22 microhms per c.c. at 20 C.

Armco Iron

Armco ingot iron is a commercially pure iron produced in the basic open hearth furnace by a somewhat similar method to that for making mild steel.

This grade of iron contains less than 0.02 per cent carbon and 0.02 per cent of manganese, with about 0.005 per cent phosphorus and 0.025 per cent sulphur with 99.93 per cent iron.

The structure consists of a plain network of grain boundaries, made up of ferrite.

Armco iron has a specific gravity of 7.866.

The specific heat at 25° C. is 0.108.

The coefficient of linear expansion is 12.6×10^{-6} for the range 20° to 300° C.

The electrical resistivity is 9.6 microhms per c.c. at 0° C.

The temperature coefficient of electrical resistivity is 0.0056 per deg. C. for the range 0° to 100° C.

The tensile strength for hot rolled rods or plates is 18.7 to 21.5 tons per sq. in. with corresponding yield points of 11.5 and 14.2 tons per sq. in. The percentage elongation is 24 to 28 per cent and reduction of area 65 to 75 per cent.

The Brinell hardness is 85 to 100.

The dead soft variety of Armco iron has a tensile strength of about 17 tons per sq. in. and Brinell hardness of 67.

Applications. Owing to its purity and freedom from included compounds this type of iron has good corrosion-resisting qualities and it is therefore used in the sheet form for exposed parts on buildings, tanks, hoarding plates, signs, etc.

On account of its purity Armco iron has excellent welding properties and is therefore used for welding rods in connection with electric and oxy-acetylene welding operations.

The joints thus obtained, when suitable fluxes are used, are sound and homogeneous.

Sheets of Armco iron are much employed for vitreous enamelled ware, since the metal is singularly free from surface defects that might otherwise affect the enamel.

On account of its ductility it is well suited to cold press and sheet metal deep-drawing operations, and is employed for parts such as baths, pots, refrigerator items, etc., which are afterwards enamelled; it can also be spun with ease.

The metal has a high magnetic permeability and low retentivity and is employed for armature core stampings, solenoid plungers, and other parts of electrical apparatus requiring such qualities.

Machining Armco Iron

Owing to the toughness and ductility of this metal it is necessary to provide cutting tools with rather different cutting and clearance

angles than for steels. The front clearance angle for turning and planing tools should be 15° to 20° , the side clearance, 12° to 15° .

Drills intended for Armco iron should have a slightly increased clearance angle with the usual 118 point angle, but with 15° clearance angle as compared with 10 for iron or mild steel. The helix angle should also be increased, the best results being obtained when the metal cuts into a continuous spiral instead of breaking into chips.

Heating Processes

Armco iron is annealed by heating to a little above the upper critical or Ar. 3 temperature for this iron, namely, 890°C ., and allowing it to cool slowly.

For hot forging purposes it is important to heat the metal to a white heat, corresponding to about 1050°C ., since it is not workable over the range 840° to 1040°C ., the latter corresponding to a bright orange colour.

Armco iron can be brazed and soldered without any difficulty by the well-established methods.

Properties of Extremely Pure Iron

Although the irons previously described attain a relatively high degree of purity it is not possible, commercially, to produce extremely pure iron, i.e. iron with less than 0.01 per cent impurities, so that the physical and mechanical properties given for the commercial irons do not represent those of the very pure metal.

In this connection tests have been made on an iron having 0.0113 per cent total impurities by F. Adcock and C. A. Bristow,* the results of which are given herewith—

Density at 19°C , 7.871 ± 0.002 g. per c.c.	
Coefficient of expansion at 25°C , 10.8×10^{-6} .	
Temperature range, deg. C.	Coefficient of expansion per deg. C.
0-100	$11.2 \pm 0.5 \times 10^{-6}$
0-150	11.8 ± 0.5 ..
0-200	12.0 ± 0.2 ..
0-250	12.4 ± 0.2 ..
Electrical resistivity at 20°C	
Cold rolled and annealed specimens	
	9.88 and 9.84 microhm/cm.
Temperature coefficient	$8.8 \pm 0.051 \pm 0.00006 t^2$
Thermal conductivity	
At 25°C	0.189 cal. cm. sec. deg. C.
At 100°C	0.176
At 150°C	0.167

* *Proc. Roy. Soc., A*, Vol. 153, December, 1935.

Critical temperatures—

	Range	Mean
Ac. 3	924–950	937° C.
Ar. 3	917–905	911° C.

Magnetic properties—

Remanence, Br	8700 Gauss
Coercivity, Hc	0.271 Oersted
Maximum permeability 14,360 at H = 0.5 Oe.	

Hardness—

Cold worked and annealed two hours at 950° C.

Brinell	2 mm./20 kg./30 sec.	49 ± 1
Diamond pyramid .	136°/10 kg./30 sec.	48 ± 3

Tensile strength—

Limit of proportionality, tons per sq. in. . . .	2.0	2.4
Ultimate stress, tons per sq. in. . . .	11.9	9.1
Elongation, per cent (l = 4 √a)	49	36
Reduction of area, per cent	100	100
Modulus of elasticity, lb. per sq. in.	29.7 × 10 ⁶	28.0 × 10 ⁶

The Ferrous Metal Range

Apart from the crude cast or pig irons and the purer forms of irons previously described, the other iron alloys derived principally from the pig irons include the refined cast irons, carbon and alloy steels, and the malleable irons. These are obtained from the pig iron by various methods of reheating and treatment.

It is not possible, owing to space limitations, to deal with the metallurgical aspect of the subject, but a general idea of the processes employed in the manufacture of steels and irons from the original iron ore may be obtained by reference to Fig. 4. It will be observed from this diagram that there are two principal processes of dealing with the blast furnace product, namely, *remelting processes*, in order to produce cast and malleable irons, and *conversion* ones for obtaining the wrought iron and steels.

The ferrous products thus obtained may conveniently be classified as follows, namely—

Wrought Iron, containing less than about 0.15 per cent carbon, which does not harden when heated and quenched.

Cast Iron, a non-malleable iron containing carbon in the combined or graphitic form, usually from about 3.0 to 4.0 (total), which does not respond appreciably to heating and quenching in the hardening sense.

Steel, consisting of iron with 0.15 to 1.5 per cent of carbon, which is malleable in one range of temperature and is capable of hardening

by heating and quenching; the hardness thus obtained increases with the percentage of carbon in the steel.

It is generally fabricated by hot forging processes, but certain grades of steel can be cast in moulds.

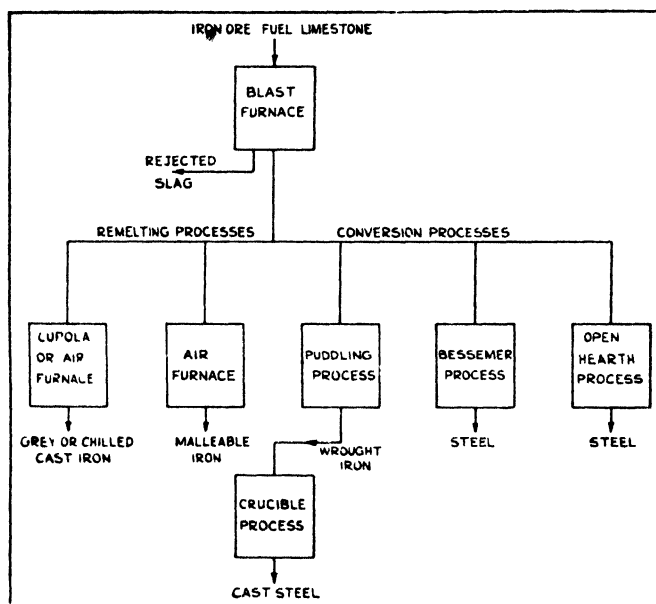


FIG. 4 SHOWING THE PRINCIPAL PROCESSES IN MAKING STEELS AND IRONS

Alloy Cast Irons

Although the cast irons previously mentioned contain small percentages of other constituents such as silicon, manganese, phosphorus, and sulphur as the result of the methods of production, it is usual to consider these as plain cast irons in order to distinguish them from the more recently developed high-strength alloy cast irons containing additional metals and elements, e.g. nickel and chromium.

Alloy Steels

The plain carbon steels hitherto considered also contain small percentages of other elements and metals as in the case of cast iron, but the carbon forms the predominating element.

Whilst these carbon steels are still widely used on account of their

general utility for ordinary purposes and their cheapness, there is now a wide range of special alloy steels having superior strength, hardness, heat-resistance and other qualities which have largely replaced the carbon steels in high-grade engineering work, e.g. automobile, aircraft, and electrical applications.

Malleable Iron

This is a malleable product which is obtained from cast iron by a process of reducing or eliminating part of the carbon of the latter so as to give a low-carbon steel or iron composition.

CHAPTER II

THE STRUCTURE OF FERROUS METALS

A good deal may be learnt about various metals and alloys by the method of examining prepared specimens through the microscope. In this way the structures of metals may be studied and information obtained regarding the different kinds of structures, the arrangement of the various constituents, their relationship to the mechanical properties of the metals, etc.

The effects of heat and mechanical treatment upon the constitution of metals, defects in metals due to incorrect heat-treatment, to inclusions of foreign matter, overstrain, and many other causes can conveniently be studied by the photomicrographic method mentioned above.

Another application of this method is in connection with the effects upon the structure of varying the proportions of given constituents in a metal (or alloy) in association, also, with the physical properties of the metal.

It is only possible, here, to give a bare outline of the photomicrographic method in so far as it affects the later references to metallic constituents and their arrangements in various ferrous materials, heat and mechanical treatments, etc.

In connection with the examination of metals which have failed, mechanically, in use, the structures of these metals near to the place of failure afford valuable information on the cause of the latter.

It is often useful to make a preliminary visual examination with the aid of an ordinary pocket lens, in order to trace zonal lines, places of growth of the fracture, slipping or relative sliding, and to determine whether the fracture is coarse or finely crystalline.

The specimens, which should measure about 1 in. square and $\frac{1}{4}$ in. thick, are usually cut in two directions mutually at right angles, and are polished in a series of progressive operations, commencing with a file, or by initial flat grinding, followed by coarse emery paper, smoother emery, and so on, down till the finest 0000 paper is reached; the next stage of fine polishing is then usually followed with the aid of a wheel covered with two layers of thick khaki cloth, with a layer of diamantine or similar polishing powder between, using a securing ring to hold the layers together. The specimen is then held against and moved across the wetted surface of the cloth whilst the wheel rotates at about

1000 r.p.m.; the pressure upon the specimen is gradually reduced until a satisfactory polish is obtained. Hard metals are more easy to polish than soft metals: the latter are sometimes cast upon glass or mica sheets, instead of polishing. Special polishing machines are now available, although hand polishing, if done properly, gives excellent results.

The specimens can now be examined directly under a microscope with objectives giving a series of magnifications from about 20 up to 2000 diameters, for the detection of impurities such as slag, porosities, sulphides, etc.

For the examination of the constitution of the metal it is necessary to employ special etching reagents, each depending upon the nature of the constituent it is required to investigate.

The principle of most of these reagents is that they act as solvents, attacking certain of the constituents of the metal more readily than others, or that they refuse to attack one or more of the constituents, thus leaving these in "relief," or that they dissolve away the joints between adjacent grains or crystals. In some cases the reagent colours one of the constituents differently from the others.

The etching reagents of the solvent type employed include nitric acid, sulphuric acid, hydrochloric acid, alcohol solutions, ammonia, sodium hydrate, etc.

Thus, the structure of pearlite in steel may be developed by using an etching reagent of 5 per cent picric acid in alcohol, whilst the difference between brittle and non-brittle steels can be readily detected by using a 4 per cent solution of nitric acid in iso-amyl-alcohol.*

Another method of preparing polished specimens is known as the *polish attack* one, and consists in polishing upon a piece of wet parchment, held on a piece of wood, and moistened with a 2 per cent solution of ammonium nitrate. precipitated chalk is also used to facilitate the polishing process. An aqueous extract of liquorice root has been employed for the polish attack method and has been successfully applied to the examination of steels for cementite, pearlite, sorbite, martensite, etc.

The method of *bas-relief* polishing consists in polishing upon a soft ground, such as leather, cloth, or rouged parchment, so that the softer constituents wear away and the harder ones stand out, polished in relief. This method yields good results in the detection of troostite, martensite, and pearlite.

* For fuller particulars of various etching solutions and methods, see *The Microscopic Analysis of Metals*, by F. Osmond and J. E. Stead.

Another method, known as *heat-tinting*, depends upon the fact that the different constituents when heated become differently tinted or coloured, the more oxidizable ones being coloured by the oxide tints. This method has been largely used by Stead, and is employed for detecting the presence of sulphur and phosphorus in irons and steels.

Constitution of Ferrous Metals

The results of microscopical examination and chemical analysis have shown that most metals have a constitution resembling the igneous and metamorphic rocks (which, like most metals, have been formed from the cooling of molten masses), consisting of an aggregation of minute crystalline fragments or particles of two or more elements or substances; each particle has a definite entity, chemical composition, and physical properties; further, there are different structure arrangements in different metals, corresponding, in the case of rocks, to the granitic, obsidian, schistose, and other types.

It has also been conclusively demonstrated that the constituents of metals and alloys behave in a similar manner to those of liquid solutions; for example, steel containing less than 0.9 per cent of carbon, and at a temperature exceeding 700° C., is a homogeneous solid solution of iron carbide (Fe_3C), known as *Cementite*, in an allotropic form of iron. When this solution is slowly cooled down it deposits pure iron, until at a certain temperature—namely, at about 670° C.—it solidifies into an “eutectic” or metallic mixture having a definite composition. If the original molten steel had consisted of more than 0.9 per cent of carbon the iron carbide would have solidified first, as cooling occurred, and at 670° C. the “mother liquor,” or pure iron, would have solidified. The resulting mixture would then have possessed a different constitution.

Definitions of Constituents

It here becomes necessary to define the different microscopic constituents of irons and steels which commonly occur. These may be classified into six principal types and others of lesser importance. The former series consists of, (a) Ferrite, (b) Cementite, (c) Pearlite, (d) Martensite, (e) Austenite, (f) Troostite. Other constituents, including Hardenite and Sorbite, have also been found.

The other constituents comprise the three allotropic forms of nearly pure iron, graphite, and slag.

(a) **Ferrite** is the name given to what is probably pure iron grains or crystals, which are very soft and ductile. These crystals are chiefly fragments of cubical crystals which develop around independent

centres of solidification, and are mutually limited by roughly plane surfaces. Low-carbon steels and wrought iron consist chiefly of ferrite.

Ferrite does not harden when cooled rapidly. It forms smaller crystals when cooled from a bright red heat at a rapid rate.

Fig. 5 shows the ferrite grains in carbonless iron, the dark spots being slag inclusions.

(b) **Cementite.** This is a definite carbide of iron (Fe_3C) which is extremely hard, being harder than ordinary hardened steel or glass.

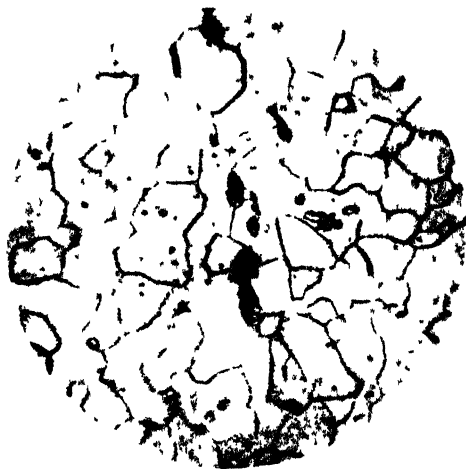


FIG. 5. NEARLY PURE IRON, SHOWING FERRITE AND SLAG INCLUSIONS (DARK PATCHES). $\times 100$

It is considered to be as hard as *felspar* (No. 6 on Moh's scale of hardness). This hardness property enables cementite to be readily detected and isolated by bas-relief polishing.

Cementite increases generally with the proportion of carbon present, and the hardness and also the brittleness of cast iron is believed to be due to this substance.

Cementite is magnetic below 205°C . Its presence in iron or steel decreases the tensile strength but increases the hardness and cutting qualities.

(c) **Pearlite** is the name given to a mixture of about 87.5 per cent ferrite and 12.5 per cent cementite, which occurs more particularly in medium and in low-carbon steels in the form of fine lamellae, which are usually curved and interstratified with those of ferrite. This mixture derives its name from the fact that it shows, with oblique

lighting, under the microscope the rainbow colours of the mother-of-pearl when the etching or polishing process has removed part of the surrounding softer ferrite

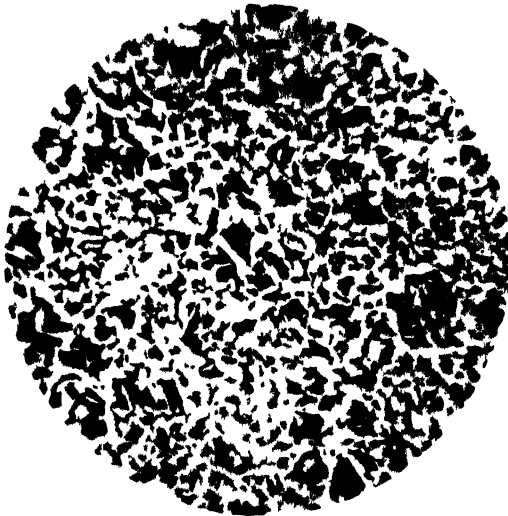


FIG. 6. 0.1 CARBON STEEL (MILD) ETCHED $\times 100$

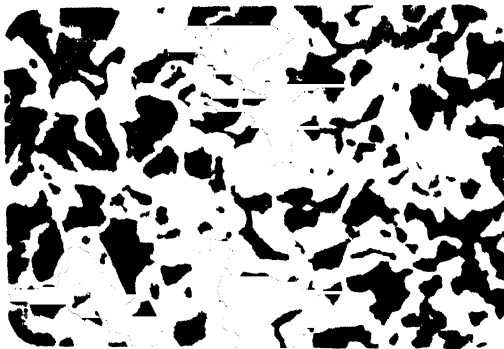


FIG. 7. STEEL CONTAINING 0.40 PER CENT CARBON, SHOWING PEARLITE AND FERRITE $\times 400$

Fig. 6 shows the darker patches of pearlite and the lighter grains of ferrite in the case of mild carbon steel. Fig. 7 shows the ferritic and pearlitic structure of 0.40 carbon steel.

It has been found that the proportion of pearlite increases from nothing in the case of pure carbonless iron up to 100 per cent, or saturation, for steel containing 0.90 per cent of carbon as shown in

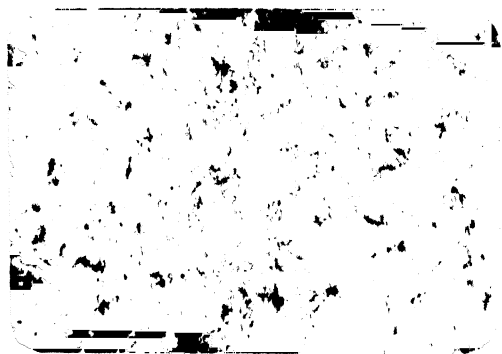


FIG. 8. STEEL CONTAINING 0.9 PER CENT CARBON. PRACTICALLY ALL PEARLITE. 400

Fig. 8, thus a 0.3 per cent carbon steel will consist of about 33 per cent pearlite, and the rest ferrite. Table I shows the relative pro-



FIG. 9. PEARLITE. 400

portions of pearlite and ferrite in carbon steels. It is characteristic of soft steels that they contain ferrite and pearlite, and that the hardness increases with the proportion of pearlite.

Hard steels are mixtures of pearlite and cementite.

In all cementation steels and steels cooled very slowly the cementite

aggregates in particles of the largest size, and is therefore more readily discernible.

TABLE 1
THE PROPORTIONS OF PEARLITE AND FERRITE IN
CARBON STEELS

Carbon	Pearlite	Ferrite	Carbon	Pearlite	Ferrite
Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
0.00	0	100	0.50	55.55	44.45
0.05	5.55	94.45	0.55	61.11	38.89
0.10	11.11	88.89	0.60	66.67	33.33
0.15	16.66	83.34	0.65	72.22	27.78
0.20	22.22	77.78	0.70	77.77	22.23
0.25	27.77	72.23	0.75	83.34	16.66
0.30	33.33	66.67	0.80	88.89	11.11
0.35	38.88	61.12	0.85	94.45	5.55
0.40	44.44	55.56	0.90	100	0
0.45	49.99	50.01			

Fig. 10* illustrates the constitution of iron-carbon compounds; the ordinates of the shaded portion *ABC* represent the amounts of pearlite present for each percentage of carbon. For steels containing less

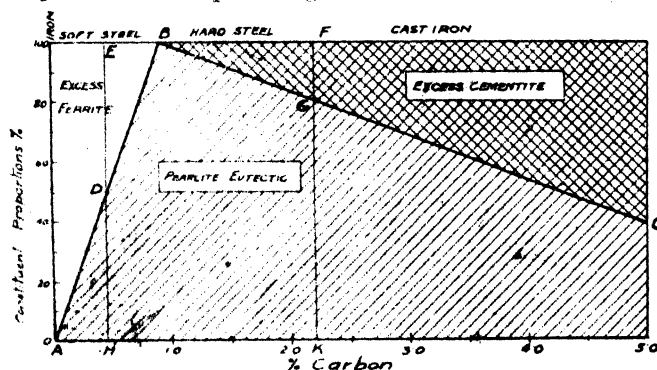


FIG. 10. IRON-CARBON COMPOUNDS

than 0.9 per cent of carbon, or "hypo-eutectic" steel, the composition of any steel containing carbon, as represented by the abscissa of the ordinate *HDE*, consists of pearlite proportional to *HD*, and ferrite to *DE*.

Similarly, for hard steels the composition represented by the ordinate *KGF* consists of *KG* pearlite, and *GF* cementite.

* Sauvenr.

(d) **Martensite.** This is the chief constituent of hardened steel and is a hard brittle mass of fibrous or needle like structure when examined under vertical light after polish attacking, and with high magnification (usually 1000 diam). It consists of iron containing carbon varying in proportions up to about 2 per cent, but hitherto it has not been possible to resolve it by the microscope into its components. When this 'solid solution' of iron and carbon contains 0.9 per cent



FIG. 11. HARDENED AIR-HARDENING STEEL. 1100X. 500

of carbon it is termed *Hardenite* and it corresponds in composition to that of pearlite or martensite saturated with carbon.

Martensite differs from austenite in being magnetic. It is not as tough as austenite.

It has been found that martensite is produced by the rapid quenching of high-carbon steel from a slightly higher temperature than the maximum temperature of the critical interval.

Martensite is found in the carbonized regions of case-hardened soft steels, hardened by quenching, but with the lower proportions of carbon the needles are longer and more definite. Fig. 11 shows the martensitic character of hardened air-hardened steel.

(e) **Austenite**, another constituent of steel, forms when carbon steel with more than 1.1 per cent carbon is quenched rapidly from about 1000° C. It consists of a solid solution of ferrite and cementite in each other.

It is hard and non-magnetic, but is not brittle. The amount of



FIG 12 TROOSTITE AND MARTENSITE IN 0.45 PER CENT CARBON STEEL. $\times 800$



FIG 13. AUSTENITE AND HARDENDITE IN 1.57 PER CENT CARBON STEEL. POLISH ATTACK. $\times 800$

austenite increases with the proportion of carbon from 0 at 1.1 per cent carbon up to 70 per cent for 1.6 to 1.8 per cent carbon.

Certain elements such as manganese and chromium in steel preserve all or some of the austenite down to 0° C.

Austenitic steels cannot be hardened by the usual heat-treatment methods and are non-magnetic.

(f) **Troostite** is another constituent of steel obtained by quenching during the critical interval or transformation period. It occurs as a slightly granular, somewhat amorphous, mammillated structure and is rather less hard and brittle than martensite. In steel quenched as previously stated it replaces the ferrite.

Troostite may also be formed by cooling the steel rapidly to form martensite and then tempering it to produce the troostite constituent.

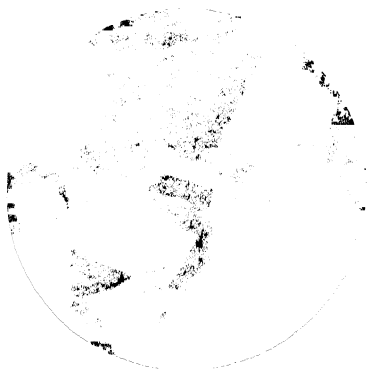


FIG. 14. AUSTENITE $\times 200$

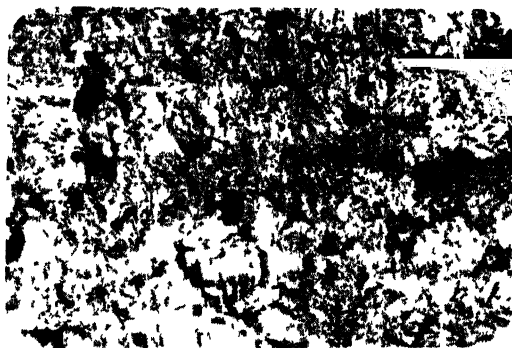


FIG. 15. QUENCHED CARBON STEEL, SHOWING BACKGROUND OF SOLID SOLUTION WITH COMMENCEMENT OF DECOMPOSITION SHOWN BY THE BLACK PATCHES OF TROOSTITE

It is also produced by cooling slowly until the transformation begins and then cooling rapidly to prevent its completion. It may be regarded as a stage in the transformation of austenite. The presence of troostite in quenched high-carbon steel is shown by the black patches, as in Fig. 15.

(g) **Sorbite** represents the product of a further stage, after troostite, in the transformation of martensite. It has good strength properties and is practically pearlitic. Sorbite is produced when steel is cooled at a fairly rapid rate from the temperature of solid solution to normal air temperature.

Some Other Constituents

There are at least three allotropic modifications in the case of pure iron—namely, α -iron, β -iron, and γ -iron, each of which has a corresponding temperature range between the Ar. 1, Ar. 2, and Ar. 3 arrest temperatures, shown in Fig. 16.

α -iron is the weak, ductile, magnetic variety, stable only below the Ar. 2 point (Fig. 16), and is characteristic of ordinary wrought iron and low-carbon steel.

β -iron is the non-magnetic kind, and is believed to be very hard and brittle, and is probably characteristic of certain self-hardening steels, such as the 7 per cent manganese steel, and of normal carbon steel which has been hardened by sudden cooling. It is stable between the Ar. 2 and Ar. 3 points.

γ -iron is also of the non-magnetic variety, and probably very hard, but ductile; it is characteristic of the 25 per cent nickel and 12 per cent manganese steels, and is stable only below the Ar. 3 point.

Graphite is a component of grey cast iron, being present in very thin flakes or laminated plates in the proportion of from 2.5 to 3.5 per cent. When such cast iron is fractured the "break" occurs through the skeleton graphite plates; and the fracture therefore appears to be almost entirely graphitic.

Slag. This impurity of furnace origin is found only in the case of wrought iron, to the extent of about 0.2 to 2 per cent, as silicate of iron. It gives the "grain" effect in the rolling process, and can be readily detected as irregular dark blotches or patches in microscopic analyses.

Hardnesses of Steel Constituents. The relative hardness of the constituents of carbon steels and irons has been investigated by Boynton, who gives the values in Table 2.

The tensile strength of pearlite itself has been shown by Professor Dalby to be about 62 tons per sq. in., and it has also been found that the tensile strength of a pearlitic steel is proportional to the sum of the pearlite tensile strength and the ferrite or iron tensile strength.

This relation may be conveniently expressed in the following form, namely—

$$f_t = f_p \cdot \frac{P}{100} + f_i \cdot \frac{I}{100}$$

TABLE 2
HARDNESSES OF STEEL CONSTITUENTS

Constituent	Product in which it is present	Relative Hardness
Ferrite . . .	Electrolytic iron and commercial wrought irons	1 to 3.6
Pearlite . . .	Series 0.13 to 1.52 carbon steel	1.8 to 10.3
Sorbite . . .	Series 0.35 to 0.86 carbon steel	3.8 to 4.2
Troostite . .	Series 0.48 to 0.58 carbon steel	5.2 to 53.6
Martensite .	Steel with 0.58 per cent carbon	88.2
Austenite . .	Series 0.2 to 1.52 per cent carbon	38.9 to 261.6
Cementite . .	White cast iron with 3.24 per cent carbon . .	103.4
	Ditto. Ditto.	272.8

where f_t is the tensile strength of the pearlitic steel, and f_p and f_f the tensile strengths of the pearlite and ferrite (or iron) respectively, and P and I are the percentages of pearlite and iron present respectively.

Substituting the values of 62 and 19 tons per sq. in.* respectively, the above expression simplifies to—

$$f_t = 0.62 P + 0.19 I \text{ tons per sq. in.}$$

Expressed in terms of the carbon content C , $P = 111.1 C$ and $I = (100 - 111.1 C)$, so that $f_t = 48 C + 19$ tons per sq. in.

These results apply only to the normal carbon steels in the annealed state.

Thermal Indications of Internal Changes in Metals

When a metal or alloy is heated progressively from atmospheric temperature up to the melting-point, certain changes in the internal condition of the metal occur at certain definite temperatures, corresponding to allotropic, isomeric, or solution changes, which are evident as heat absorptions or “arrests” on the temperature-time curve.

There are two types of changes which occur in the structure when the temperature varies at a uniform rate—namely, continuous and critical changes; the latter correspond to a sudden modification in the normal condition between a certain property and temperature. On temperature-time heating and cooling curves such changes are represented by discontinuity or the intersection of two branches of the curve.

The temperature scale is divided into a number of intervals by these critical changes, each interval corresponding to some internal

* *Journal Iron and Steel Institute*, 1906, p. 287.

change in the constituents; each metal must experience at least two such changes—namely, those corresponding to fusion and volatilization—but in many instances, such as in the cases of iron, steel, and non-ferrous alloys, other intermediate points of transformation occur.

These thermal changes are valuable indications of the micrographic structural arrangements.

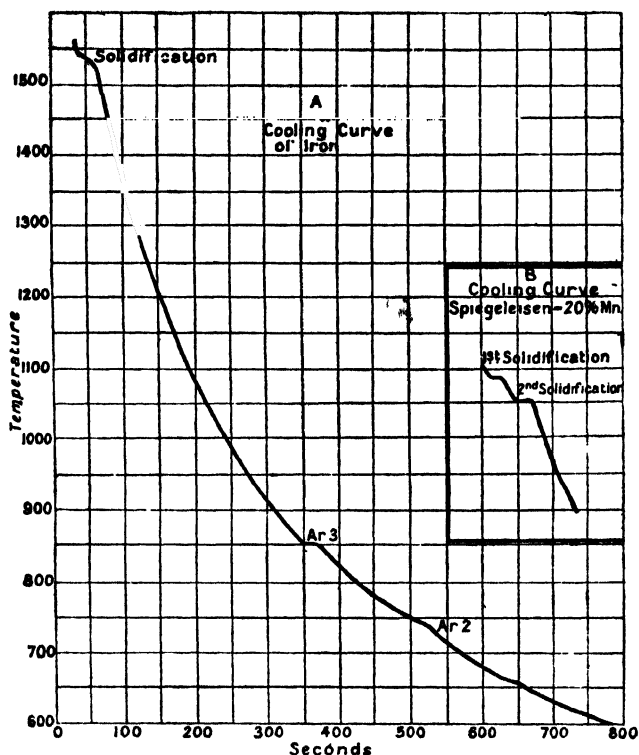


FIG 16 COOLING CURVE OF PURE IRON

Pure Iron Curves

When practically pure iron is left to cool from the molten state, and the temperatures are plotted as ordinates at equal intervals of time—say every ten seconds—the cooling curve obtained will be found to resemble that shown in Fig. 16.* It will be seen that there is one critical point at about 1530° C. corresponding to solidification.

* Osmond, *The Microscopic Analysis of Metals*.

The first "arrest," known as the Ar. 3 point, occurs at about 860°C ., and represents an allotropic transformation, whilst the Ar. 2 point, which occurs at about 750°C ., marks another allotropic transformation or change in the material, accompanied by a change, with further cooling, from the non-magnetic to the magnetic condition; at each of the arrest points evolutions of heat occur, which correspond to a yielding up of energy. The next arrest (not shown in Fig. 16), known as the Ar. 1 point, occurs at about 690°C .

The above example is somewhat analogous to the case of water solidifying into ice and yielding up its latent heat of "fusion" in the process.

The effect of the presence of any impurities, even in a very small quantity, is to lower (and often to smooth out) the arrest points; for example, these points are invariably lower for iron containing carbon than for pure iron.

Bodies which are mixtures of several constituents will have several solidification points, each corresponding, as a rule, to one of the constituents. The inset diagram in Fig. 16 shows the two solidification points for spiegeleisen, which is an iron containing about 20 per cent of manganese, at 1085°C . and 1050°C . respectively.

When iron is slowly heated right up to its fusion point, absorptions instead of evolutions of heat occur at the critical points, the latter, however, occur at rather higher temperatures (usually from about 40° to 60° higher) than the arrest points obtained by cooling.

The Critical Points in Steel

The term "critical point" is employed to denote the temperature at which a change in the microstructure and physical properties of a metal occurs during heating or cooling. The critical points are determined by sensitive and accurate pyrometers.

When carbon steels are allowed to cool very slowly from a high temperature several critical or "arrest" points are observed, corresponding to evolutions of heat which indicate a change of constitution; thus there is one condition of the metal above, which gives place to a different phase below, this temperature. The change of phase that occurs is always accompanied by an alteration of physical properties, e.g. structure, density, hardness, etc.

A typical cooling curve for steel is shown in Fig. 17 (A). The first arrest corresponds to the beginning of the formation of a new constituent; the change of slope of the curve on further cooling denotes that more of this new constituent is being thrown out of the solid solution which exists in the range above the first critical point.

The second arrest is more marked and is particularly noticeable as the carbon content is increased; it corresponds with the formation of pearlite. The recalescence effect of this change point can be observed

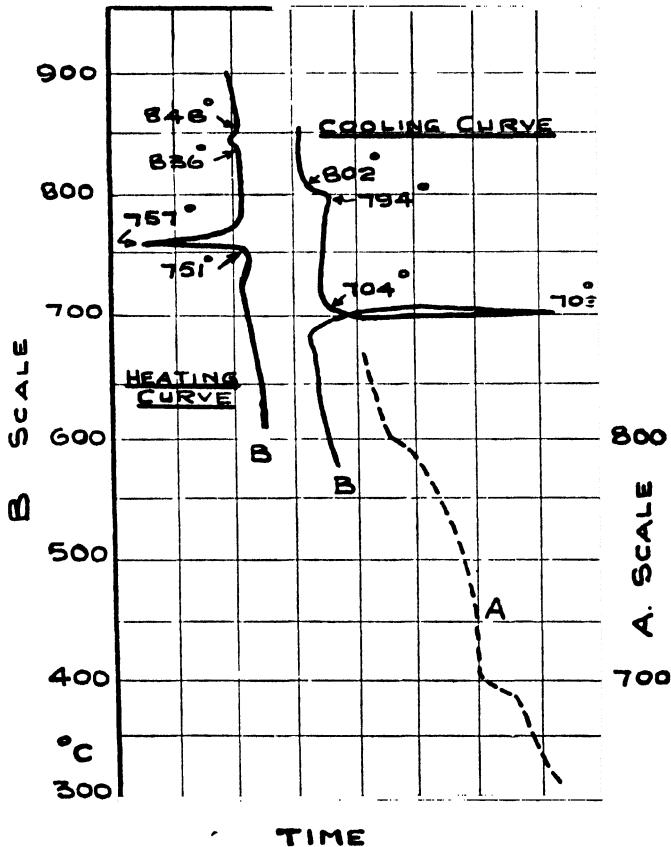


FIG. 17. ORDINARY (A) AND INVERSE RATE (B) CURVES

visually when a rod of high-carbon steel is allowed to cool from a bright yellow heat in a darkened room. When the rod appears almost to have lost its red colour it suddenly commences to glow again, due to the evolution of latent heat producing a rise in temperature; thereafter, cooling occurs progressively.

On heating a steel the reverse of these effects occurs, heat being

absorbed to complete the solution of the constituents; this is evident as a lag in the heating curve.

A more accurate method of observing the critical points is to plot the heating and cooling curves in terms of the time taken per degree rise or fall of temperature; this is known as the *Inverse Rate* method. It shows the initial, maximum, and final points of the change in greater detail. Fig. 17 (*B*) shows typical inverse rate heating and cooling curves for a 0.45 per cent carbon steel. It will be seen that there is a difference of about 50° C. between the recalescence point on the cooling curve and the reverse or *decalescence* (heat absorption) point on the heating curve. This indicates that once the critical temperature has been exceeded on heating the reverse change does not begin until the temperature falls some 50° C. A deduction from these results is that for *heat-treatment processes* it is of the greatest importance that the temperatures used should be in excess of the heating curve critical points.

It should here be mentioned that the heating curve arrest points, denoted by the letters *Ac*, are distinguished from the different cooling curve ones by using the letters *Ar* for the latter.

When the critical points obtained in a series of iron-carbon alloys are interconnected the *equilibrium diagram* is obtained; the lines on these confine areas of definite metallographic and physico-chemical constitution so that by reference to such a diagram the constitution of any steel at any given temperature can be ascertained. For all carbon contents the same change takes place on heating or cooling past a given line on the equilibrium or liquidus-solidus diagram; the only difference is the temperature at which the change occurs, this varying with the constitution.

Fig. 18* shows the heating and cooling curves for iron and the various steels mentioned in the caption below. The full lines denote the cooling and the dotted lines the heating curves.

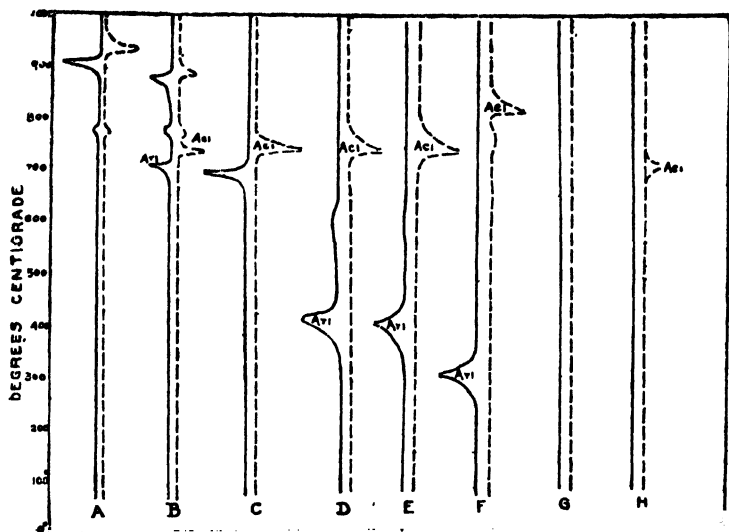
The heating and cooling curves for mild steel and stainless iron and steels† are given in Fig. 19 for the purposes of comparison.

The martensitic steels shown in (1) and (2) have well-marked carbide change or arrest points, a fact that indicates the necessity for using high hardening temperatures to obtain the desired structures.

The S.80 stainless steel (4) has rather indeterminate change points, whilst in the austenitic steels (5) and (6) there are no critical points, so that the austenitic or "solid solution" character of these steels occurs at all temperatures from those shown in Fig. 19 down to normal air temperature.

* From Dr. Hatfield's "Steels used in Aero Work," *Aeron. Journ.*, 1917.

† Firth-Vickers Ltd.



ABSORPTIONS AND EVOLUTIONS OF HEAT WITHIN THE STEELS DURING HEATING AND COOLING.

FIG. 18. HEATING AND COOLING CURVES FOR STEELS

--- HEATING CURVES

— COOLING CURVES

A — pure iron

D — high-tensile steel

G — 25 per cent nickel steel

B — case-hardening steel

E — air-hardening steel

H — manganese steel

C — carbon steel

F — stainless steel

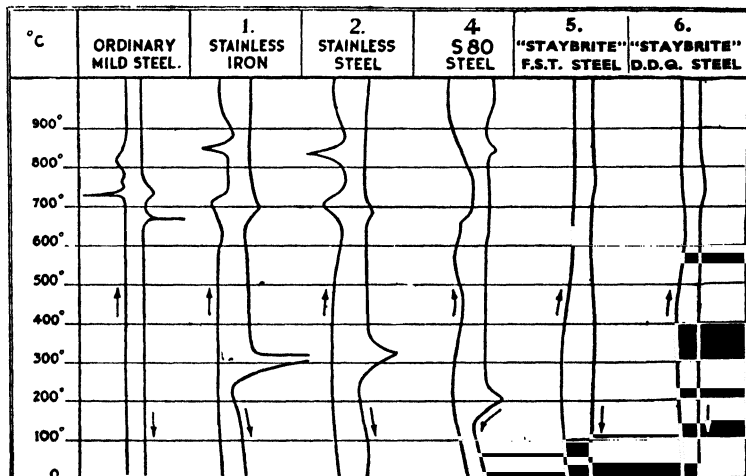


FIG. 19. HEATING AND COOLING CURVES FOR STAINLESS IRON AND STAINLESS STEELS

In the example shown in curve *B*, Fig. 18, for case-hardening carbon steel, when the temperature is a little over 700°C ., the pearlite constituent is changed into a homogeneous substance, which is a solid solution of iron carbide. This critical change is accompanied by an absorption of heat which is evident upon the temperature curve *B*, as an arrest point, and which is not shown upon the pure iron curve *A*.

The magnetic change point still occurs at the same temperature—namely, at about 770°C .—but the allotropic change point, *Ac*. 3, occurs at a much lower temperature.

In the case of the 0.6 per cent carbon steel, the temperature curves (*C*, Fig. 18) show that the upper critical points have been lowered, and are apparently joined up with the carbon change points at about 730°C .

In this steel the major portion—namely, two-thirds—consists of the constituent pearlite, and hence it would be expected that the corresponding critical points to those of pure iron would be lowered (in temperature) and would be more marked; curve *C* shows that this is the case.

The heat absorption, corresponding to solution during heating, occurs at 730°C ., whilst the evolution of heat during cooling, which is associated with the solidifying of the ferric carbide solution, takes place at about 700°C .

Referring to curve *G*, Fig. 18, it will be seen that no critical points occur during cooling, or heating, over the usual range of working temperatures; it is for this reason that the 25 per cent nickel steel alloy is non-magnetic, its condition corresponding to the solid solution state.

Similarly, in the case of 12 to 14 per cent manganese steel, if heated up from the untempered state, and cooled sufficiently quickly, it retains the “solid” state and shows no critical points. In the tempered state an arrest point is, however, evident, as shown in curve *H*, Fig. 18, in the neighbourhood of the carbon change point; the cooling curve will not, of course, reveal any corresponding critical point. When this type of steel is cooled sufficiently rapidly it is found to be non-magnetic.

Solidification Curves

It has already been stated that metals under varying temperature conditions behave in a somewhat similar manner to liquid solutions; this resemblance will here be considered more fully.

When a solution of salt and water is progressively lowered in temperature it will be found to begin to freeze at a lower temperature than that of water alone. If a number of such solutions containing different

proportions of salt and water be taken, and their initial freezing-points be plotted against their percentage compositions, curves similar to *ME* and *EN* (Fig. 20) will be obtained.

Consider any solution, such as represented by *PQR*, containing 90 per cent of water and 10 per cent salt. When the temperature reaches the value denoted by *P*—namely, -9°C .—the solution begins to freeze, and in consequence of the ice separating out first the remaining liquor becomes richer in salt, thereby causing a lowering of its freezing-point along the line *PE*, ice separating out the whole time, until at -22°C ., the “mother-liquor” remaining, which consists of about 23.5 per cent of salt, freezes bodily. Similarly, if a solution containing more than 23.5 per cent of salt, as represented by the point *P*¹, be cooled, salt will separate out when its temperature reaches the value represented by *P*¹, and will continue to separate out along *NE*, causing the remaining liquor to become progressively weaker in salt, until, as before, at -22°C . the remaining solution will solidify bodily without further separation.

Similar phenomena occur in the case of alloys such as the ferrous and non-ferrous ones when cooled from the fusion point.

Iron-carbon Equilibrium Diagram

The iron-carbon equilibrium diagram is shown in Fig. 21 for steels up to 1.2 per cent carbon. Above the lines *Ac. 3*, *Ac. 3. 2* and *Ac. cm.* martensite exists.

When 0.2 per cent carbon steel is heated to just above 850°C ., i.e. above the *Ac. 3* point, and quenched, the ferrite and pearlite of the original annealed steel give place to the hard needle-structure constituent martensite. In general the microstructure of any particular point on the equilibrium diagram can be preserved by rapid cooling from that point, as by quenching in cold water.

Slow cooling of 0.2 per cent carbon steel, corresponding to annealing, gives a microstructure consisting of ferrite and pearlite.

If the 0.2 per cent carbon steel is heated to 850°C . and allowed to cool slowly to 800°C ., a temperature below the *Ar. 3* line on the dotted cooling curve (Fig. 21), and then quenched, the microstructure is one of crystals of ferrite in martensite background. If quenched from a temperature of 710°C ., i.e. just above the *Ar. 1* line, the ferrite crystals are much more numerous, being almost completely separated out, but the background is still martensite which has become saturated with the dissolved carbide. At the *Ar. 1* point the martensite solid solution always contains 0.9 per cent carbon, which corresponds to the maximum it can hold at this temperature.

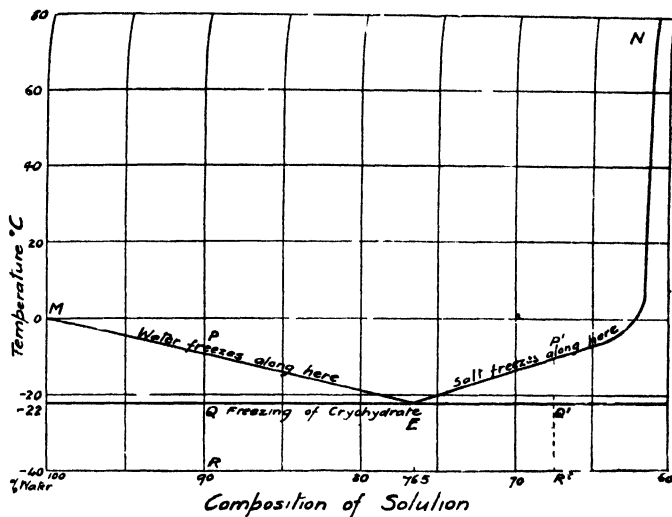


FIG. 20. SALT SOLUTION CURVES

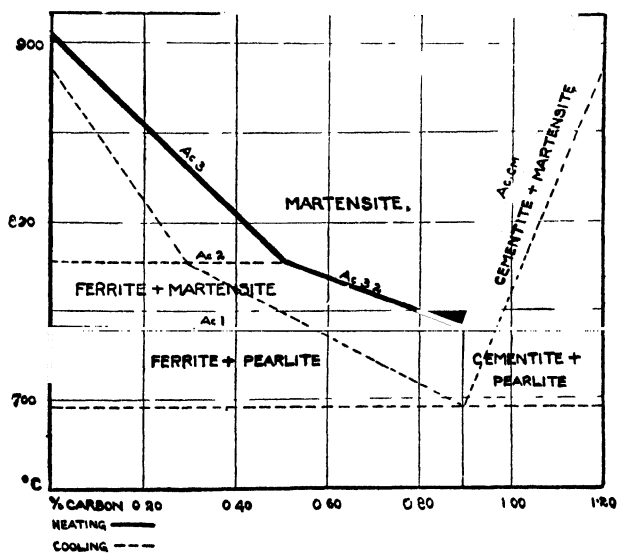


FIG. 21. IRON-CARBON EQUILIBRIUM DIAGRAM

As the percentage of carbon increases from 0 to 0.9 per cent the needles of martensite become smaller and less distinct and the hardness and tensile strength increase on quenching.

It has been shown that the constitution or microstructure of the 0.2 per cent carbon steel is governed by the quenching temperature, but below the Ar. 1 point (about 695° C. in Fig. 21) there is no alteration due to quenching, so that the normal ferrite-pearlite structure of annealed steel is maintained.

Similar changes occur in all steels containing less than 0.9 per cent carbon, but as the carbon content increases the temperature at which the ferrite is first thrown out of solution is progressively lowered. An important deduction from these results is that *the temperature required to bring about complete solution of all the constituents varies inversely as the carbon content*. For this reason low-carbon steels require heating to a higher temperature than higher-carbon steels for hardening, annealing, normalizing, etc. In this connection the Ac. 3 line is the most important one on the equilibrium diagram for heat-treatment processes.

Tensile Strength and Constitution

In regard to the specific example of 0.2 per cent carbon steel which has been considered, the effect of quenching from various temperatures has been shown to influence the constituents of the steel in the cold condition. These different constituents, corresponding to definite microstructures, are related to the tensile strengths of the steel as the results given in Table 3* indicate. The values given were obtained by heating rods of 0.2 per cent carbon steel of $\frac{1}{4}$ in. diameter to 850° C., and after cooling to the temperatures stated in the table, quenching at these temperatures.

0.9 Per Cent Carbon Steel

Steel containing 0.9 per cent—or more correctly 0.89 per cent—carbon has the lowest solidification point of all the carbon steels and is the iron-carbon eutectic. Only one critical change is possible for such a steel, namely, the transformation of martensite to pearlite at 695° C. for slow cooling from above this temperature.

The structure of this steel depends, however, upon the rate of cooling, and in this connection it has been shown by Prof. Carpenter† that when such steel is cooled more or less rapidly from 750° C. the structures are as indicated in Table 4.

* "The Steels," *Workshop Practice* (Pitman).

† *Alloy Steels*, Prof H. C. H. Carpenter. Cantor Lectures, 1927–8, Royal Society of Arts.

TABLE 3
EFFECT OF HEAT-TREATMENT ON TENSILE STRENGTH

Treatment	Tensile Strength in tons per sq. in
Heated to 850° C. and water quenched	90.90
Cooled from 850° C. to 800° C. and water quenched	72.20
Cooled from 850° C. to 750° C. and water quenched	63.00
Cooled from 850° C. to 705° C. and water quenched	50.25
Cooled from 850° C. to 640° C. and water quenched	30.80

TABLE 4
EFFECT OF COOLING 0.9 PER CENT CARBON STEEL AT
DIFFERENT RATES

Rate of Cooling	Structure	Change
Most rapid chilling possible	Austenite*	None
Rapid chilling	Martensite	Gamma to Alpha only
Slower chilling	Troostite	Gamma to Alpha + carbon formation
Still slower chilling	Sorbite	ditto
Cooling at ordinary rates	Pearlite	ditto

Although hitherto no one had succeeded in chilling 0.9 per cent carbon steel from 750° C. so rapidly that the *gamma* to *alpha* change was completely prevented, it has been possible in the case of certain alloy steels.

Higher-carbon Steels

When the carbon content exceeds 0.89, cementite becomes a constituent and it behaves in a somewhat similar manner to ferrite in the lower-carbon steels in that it is capable of forming a complete solution on heating, from which it separates again when cooled.

Thus, when 1.4 per cent carbon steel is quenched at 695° C., i.e. during the Ar. 1 transformation, its microstructure shows that there is martensite changing to pearlite and at the grain boundaries a cementite network. When this same steel is quenched from 1100° C., i.e. above the temperature of martensite solid solution (or above the right-hand inclined dotted line in Fig. 21), the structure consists of another constituent, namely, *austenite* mixed with martensite; the

* This has not been entirely realized. Mixtures of austenite and martensite are obtained.

former constituent is the true solid solution of carbon or carbide in iron, but is difficult to obtain by quenching so that martensite is invariably associated with it.

In regard to the Ac. 2 line in Fig. 21, this is conjectured to correspond to the two allotropic modifications or transformations of iron.

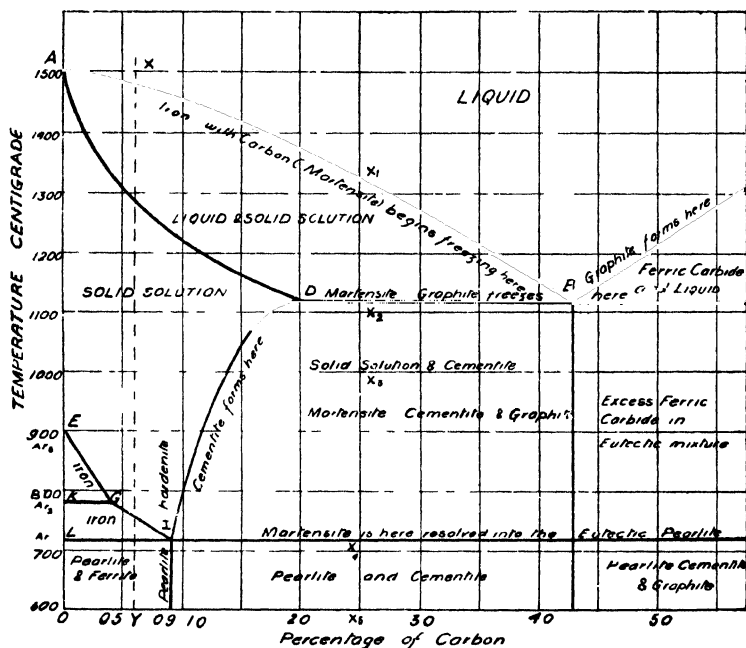


FIG. 22. EQUILIBRIUM CURVES FOR IRON AND CARBON

Thus, the Ac. 3 and Ac. 3.2 branches are believed by some investigators to correspond to the two allotropic forms of iron, although this subject is a somewhat controversial one; it has little practical significance.

Equilibrium Diagram for Iron and Carbon

The complete diagram shown in Fig. 22 is obtained by plotting, as temperature ordinates, the arrest points of a very large number of iron-carbon alloys, varying in constitution from pure iron ($C = 0$ per cent) up to cast iron ($C = 5$ per cent), through the range of carbon steels. It should be emphasized that the curves of equilibrium shown correspond with the arrests upon the cooling curves of these materials.

One or two of the lines upon the diagram, however, have been obtained or confirmed by indirect methods.

The line *AB* shows that as the proportion of carbon increases from nothing to about 4.3 per cent, the melting-point falls from about 1500° C. for pure iron at *A* down to 1140° C. for the eutectic, or pure pig iron, at *B*. The fusibility of cast irons is evident from this fact.

Below 720° C. the solid solution solidifies into pearlite or cementite, as indicated by the horizontal line *LH*, at practically the same temperature over the whole carbon range. If any vertical line, such as *XY*, be drawn upon the diagram, the manner in which it cuts the equilibrium curve will determine the constitution of the corresponding carbon content steel; for example, in the case of *XY*, which corresponds to 0.6 per cent of carbon, it will be seen that solidification commences at about 1460° C., and is followed by complete solidincation where *XY* cuts *AD*. This mass then cools down until it reaches the point where *XY* cuts *GH*—that is, to a temperature of about 760° C.—when a small amount of γ and α allotropic forms of iron separates out.

The Roberts Austen carbon-iron diagram gives the line *LH* just below the 720° C. line—namely, at about 685° C.—and in a general way divides the “Percentage of Carbon” range into two parts as follows: from 0 to 2.1 per cent carbon is classed as “Steel,” and from 2.1 to 6.67 per cent carbon as “Cast Iron.”

At about 20° to 30° lower temperature, when the line *LH* is reached, pearlite separates out, and the whole mass becomes a solid steel, containing a large proportion of pearlite, in which small ferrite areas occur.

With a lower carbon content, greater ferrite areas will occur.

The effect of rapid cooling from the solid solution region will be to retain in the solid metal much austenite.

High-carbon Metal

Consider the case of iron with 2.5 per cent of carbon cooling from the molten state; this combination approaches the limits of cast iron, since it only requires about 2 per cent of carbon to saturate solid γ -iron; the martensite, which continues to solidify from about 1280° C., rejects all carbon in excess of this quantity, and leaves it in the remaining molten mother-liquor.

This process continues from the point X_1 to X_2 (Fig. 22)—that is, until a temperature of about 1125° C. is reached, when the carbon content of the mother-liquor reaches about 4.3 per cent; as further cooling occurs below the line *DB* the mother-liquor solidifies bodily into an eutectic mass of graphite and martensite.

When the temperature of $1000^{\circ}\text{C}.$ is reached at X_3 part of the graphite unites with some of the iron, to form cementite, and the mixture between X_2 and X_3 therefore consists of martensite, cementite, and graphite. At X_4 this martensite, which has now become hardenite, splits up into pearlite, so that the resulting metal contains pearlite, cementite, and graphite, after cooling down to the completely solid state.

Alloy Steels

The presence of elements in steel, such as *nickel*, *chromium*, *tungsten*, and many other elements, tends to alter the solidifying and critical points in exactly the same manner that the presence of carbon does.

The critical points are lowered by both *nickel* and *manganese*, as the curves given in Fig. 18 clearly show. Thus, with 25 per cent of nickel, or 12 per cent of manganese, the Ar. 3 point is lower; such steels are characterized by the presence of martensite similar to rapidly cooled carbon steels, and normally consist of γ -iron modified by the large amount of manganese or nickel with which it is alloyed.

It should be mentioned here that in carbide of iron (Fe_3C) the iron is capable of being partially replaced by other elements, such as those present in alloy steels.

The two special nickel and manganese alloy steels above mentioned are non-magnetic.

Referring to Fig. 18 again, it will be seen that in the case of *nickel-chrome steel* (curves *D* and *E*) the change to the solid solution state, with heat absorption, occurs at about the same temperature during heating as in the case of the carbon steels, but the *arrest points* occur at an appreciably lower temperature during cooling. For this reason the effect of the elements nickel and chromium is to make the carbon change more sluggish—that is to say, more easily controlled and suppressed—so that larger masses of this alloy steel can be satisfactorily heated and hardened.

In the case of *air-hardening steels*, the speed of cooling which results from the air-hardening process is sufficiently rapid to suppress the carbon change, and to cause the mass to retain its solid solution state.

Figs. 11 and 23* show the structures of this type of steel in the hardened and annealed states respectively.

With the alloy steels it is easier to obtain the “solid solution” state, and this usually occurs with heat evolution during cooling at a lower temperature. It should be pointed out that if the thermal change point can be suppressed by quenching, rapid cooling, or

* Dr. Hatfield.

otherwise, the breakdown from the solid solution to the pearlitic condition is prevented.

In the case of *manganese steel*,* when the percentage of manganese lies between about 12 and 14, the cooling curve, from the molten state, shows no "arrest," and the solid solution state can be readily preserved by a sufficiently rapid cooling. Thus, if this high-manganese steel be

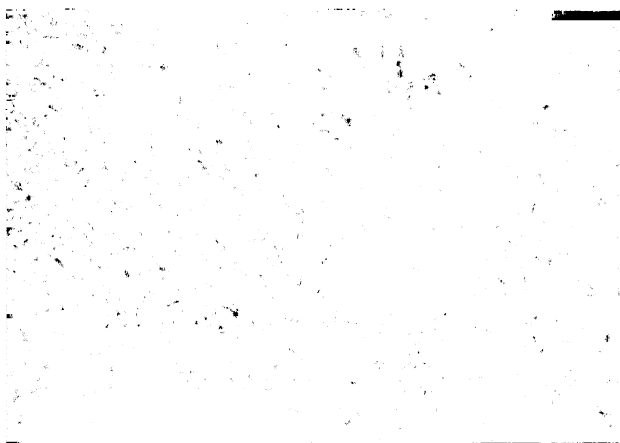


FIG. 23. ANNEALED AIR-HARDENING NICKEL-CHROME STEEL.
ETCHED. $\times 500$

quenched at about 950° C. a non-magnetic and tough condition results (Fig. 24).

High-nickel steel, containing about 25 per cent of nickel, is also non-magnetic, for no absorptions or arrests of heat occur during heating or cooling in the ordinary range of working temperatures met with commercially, so that the solid solution state, modified only by the high percentage of nickel present, is obtained.

The microstructure of this steel, in its best condition, consists of polygonal grains or allotromorphic crystals of solid solution of carbide of iron and nickel, in iron containing nickel.

In *air-hardening nickel-chrome steels* the effect of the particular proportions of nickel and chromium is to render the speed of cooling quick enough to suppress the carbon change point and to present the solid solution state, in which the material at ordinary temperatures is extraordinarily hard and tough.

* Discovered by Sir R. A. Hadfield.



FIG 24 MANGANESE STEEL MICRO ETCHED $\times 100$



FIG 25 MAGNET STEEL (TUNGSTEN) ETCHED $\times 500$

The Time Factor

It has been shown that much of the diversity of opinion about the exact effect of certain elements, e.g. chromium, upon steel has been due to the omission to take account of the rate of cooling, or the time-factor effect, when studying the results of investigations. It has been shown, for example, that, in the case of a chromium steel containing a little over 6 per cent of chromium and 0.63 per cent of carbon, when specimens were heated to 1000° C. and allowed to cool (a) in still air, on an asbestos pad, taking thirty minutes to reach atmospheric temperature, and (b) in the furnace, taking sixty minutes to reach ordinary temperatures, in Case (a) the Brinell hardness was 642, whereas in Case (b) the hardness was only 281. Thus the steel became what is known as "self-hardening" in the one case and "soft" in the other, due to the different rates of cooling.

Table 5 shows the influence of the time factor upon the hardness of the above-mentioned chrome steel when cooled from an initial temperature of 1200° C. In connection with these results, it was observed that with the slower rates of cooling the critical temperatures were higher, but the rises of temperature, or heat evolutions, were much greater; as the cooling rate increased, so the critical points became lower and less marked, until, with a rate of about two minutes,

TABLE 5
EFFECT OF COOLING RATE UPON HARDNESS OF CHROME
STEEL. (C = 0.63, Cr = 6.18 per cent)

INITIAL TEMPERATURE, 1200° C.

Cooling rate in minutes	min. sec		min. sec		min. sec		min. sec		min. sec	
	min.	sec.	min.	sec.	min.	sec.	min.	sec.	min.	sec.
	19	8	16	28	12	33	12	8	8	51
	---	---	---	---	---	---	---	---	---	---
Brinell hardness	333		337		398		503		632	
									664	
									680	

there was no noticeable carbon change point, and maximum hardness (Brinell 680) occurred. The more rapid cooling rates cause the carbon change points to be entirely suppressed, and microphotographs of chrome steels cooled at different rates show that the constitution, as the rate of cooling is increased, corresponds to increasing percentages of solid solution carbon—that is to say, to greater proportions of austenite, martensite, or hardenite.

Chromium Steels

Steels containing chromium have assumed such an important position in engineering and industrial spheres that a few further remarks upon their characteristics and structures may be of some interest.

Apart from the stainless steels, containing from 7 to 15 per cent of chromium, there is a much older known range of low-chromium steels, having from 1 to 8 per cent chromium, of important application. The compositions and properties of the more useful chromium steels are dealt with later on in this volume. It is an interesting fact that the melting-points of iron and chromium are very nearly the same; iron melts at 1535°C . and chromium at 1525°C . In the molten condition chromium and iron mix together very readily; moreover, they have the same crystal lattice, namely, a body-centred cube.

As Professor H. Carpenter has pointed out,* in contrast to tungsten, chromium does not lower the pearlite inversion in carbon steels, but actually raises it.

In Table 6 the Ar. 1 change temperatures are given for a carbon and three chromium steels, all cooled from 900°C .

It will be seen from these results that the temperature of the change to carbide carbon, i.e. pearlite, is progressively raised with the chromium content.

TABLE 6
PROPERTIES OF CHROMIUM STEELS

Percentage of Chromium	Constituent	Temperature of Ar. 1 Inversion $^{\circ}\text{C}$.
0	Pure pearlite	715
1.10	Chromiferous pearlite . . .	729
3.24	Chromiferous pearlite . . .	758'
9.55	Chromiferous pearlite . . .	776'

Another interesting feature of chromium is that the temperature of the Ar. 1 inversion is practically independent of the temperature from which the steel is cooled.

Steels containing high percentages of chromium, e.g. 30 to 35 per cent, generally show martensitic structures unless they are cooled at a very slow rate; thus on careful annealing the martensite changes to the carbide carbon structure.

* *Alloy Steels*, Professor H. C. H. Carpenter. Cantor Lectures. Royal Society of Arts, 1928.

Fig. 26 shows the constitution of chromium steels for the range 0 to 18 per cent chromium and 0 to 2.8 per cent carbon.

When low-chromium steels of suitable carbon content are quenched they exhibit extremely hard structures; for this reason these steels are used for files, ball-bearings, and steel rolls (for mills).

The hardness in this case is no doubt due to the properties of chromiferous martensite, and possibly to the existence of hard carbides.

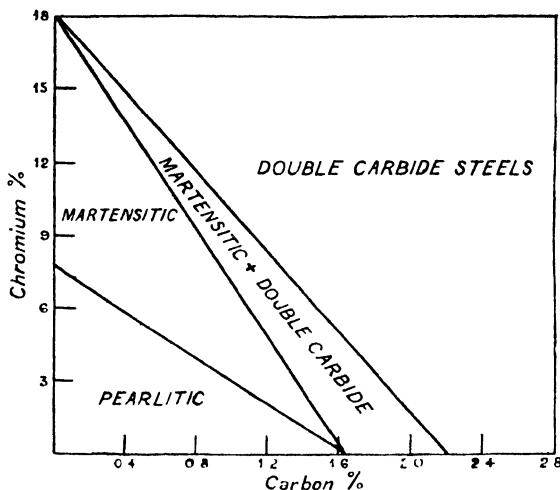


FIG. 26 CHROMIUM STEELS STRUCTURAL DIAGRAM (Guillet)

In the case of the class of chromium steels known as *stainless steels*, the structure is essentially that of a chromiferous martensite; the hardening temperature is about 100° C. higher than that of a pure carbon steel, due to the effect of the chromium raising the Ac. 1 point.

It is considered essential in stainless steels to have no free carbides, for the corrosion resistance of this steel—which is a low-carbon high-chromium steel—depends upon the whole of the carbon being dissolved.

Nickel Steels

When nickel is present in carbon steel it is soluble in all proportions at elevated temperatures in both the liquid and solid states. At normal temperatures nickel is in solid solution in the iron. Nickel steels, after slow cooling, may have pearlitic, martensitic, or austenitic structures, depending on the nickel and carbon contents. Fig. 27, which is based on Guillet's results, shows the composition ranges of

the three different groups of nickel steels. With increased cooling rates, the structure at any composition will change in a manner similar to that brought about by increasing the carbon or nickel content.

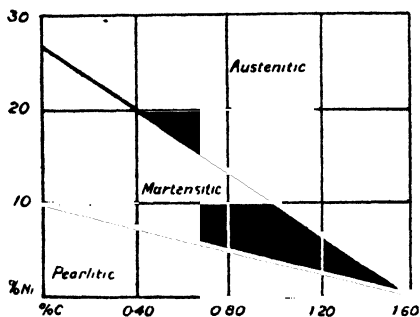


FIG. 27. COMPOSITION RANGES OF NICKEL STEELS

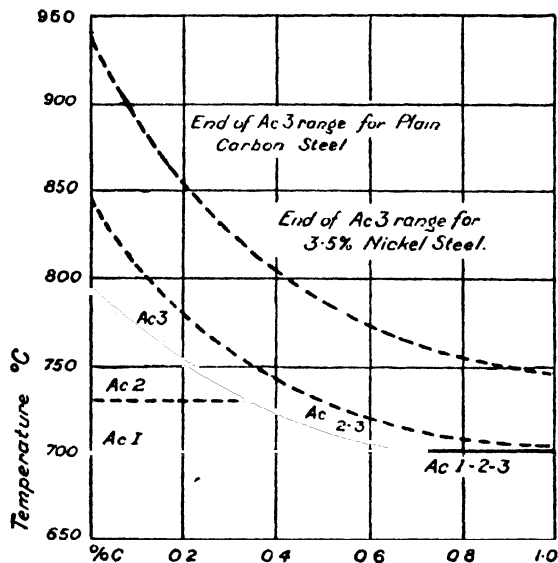


FIG. 28. EFFECT OF NICKEL ON THE LOWERING OF THE CRITICAL POINTS

For nickel steel with up to 5 per cent nickel, each one per cent of nickel lowers the Ar. 1 critical point from 10–20° C. below those of a corresponding straight carbon steel; and the Ac. 3 point from 8 to

14° C. The lower the carbon content, the greater is the depression of both Ac. 3 and Ar. 1. With a nickel content of 32-33 per cent, the Ar. 3.2 point is apparently depressed to absolute zero. This makes it impossible to harden these high-nickel steels by quenching.

The 25 per cent nickel steel has its Ar. 3.2 point at about atmospheric temperature so that this alloy steel is non-magnetic at ordinary air temperatures. In general the 20-30 per cent nickel steels are *non-magnetic* if cooled at normal rates from forging temperatures.

Fig. 28 gives a general idea of the lowering of the critical points of steel by the addition of nickel.

These curves should be accepted as indicating only the general effect of nickel and, in view of the conflicting data available to-day, do not represent the precise values of these critical points. The addition of nickel also reduces the eutectoid carbon ratio from 0.9 per cent for straight carbon to about 0.75 per cent for 3.5 per cent nickel and about 0.70 per cent for about 5 per cent nickel.

CHAPTER III

CAST IRON

THE pig iron as originally produced from the blast furnace is remelted in special air or cupola furnaces, where its carbon content is adjusted to the desired amount, and other constituents, e.g. silicon, manganese, sulphur, and phosphorus, regulated to the specification decided upon. The cupola furnace, resembling a small blast furnace, is charged with pieces of coke and pig iron until nearly full, and a blast of air forced through tuyeres near the bottom burns the coke; the heat thus developed melts the iron, which is tapped or run off down a spout into the sand moulds. The slag is removed from the slag spout situated a little higher up than the iron spout.

The air furnace previously referred to is a reverberatory one similar to a puddling furnace, but larger. In this case the pig iron is placed on the bottom, or hearth, and is melted down by the heat of the fuel. When molten, any excess of carbon is burnt away to give the desired proportion.

Cast iron has a high carbon content, usually between 3 and 4 per cent in ordinary casting grades; its limits, however, lie between about 2 and 6·7 per cent. Owing to its ease of melting and fluidity when melted, it can readily be cast economically into intricate shapes in various sizes. It is usually cheaper to make iron castings of difficult shapes than to employ fabricated wrought iron or steels.

Plain Cast Iron Applications

The various kinds of commercial castings in iron require different compositions, depending upon the particular uses to which they are to be put. Thus, iron intended solely for ornamental purposes must be very fluid when melted and able, when it has cooled in the mould, to take sharp impressions, so that little or no machining work is required for finishing the parts; this latter quality indicates the use of an iron that will expand in solidifying, thus taking a sharp impression of the mould.

Cast iron for engineering purposes must be strong, but not too brittle. For machinery parts, e.g. brackets, bedplates, beds, slides, bases, pedestals, etc., the iron must be soft enough to allow it to be machined with ease; in this case sharp impressions, or shape in casting, are secondary to machinability.

Iron for water pipes must be close-grained and able to be run into thin sections without contraction strains.

Again, the iron used for hydraulic and steam cylinders must be very fine-grained and strong so that it will withstand high pressures without failure or leakage.

Internal combustion engine cylinder and piston irons must also possess the combination of strength, hard wearing surface, and easy casting properties for the intricate shapes and thin sections used. For

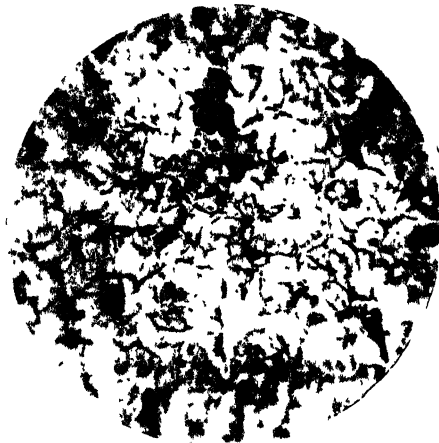


FIG. 29 GREY OR WEAK CAST IRON ETCHED $\times 50$

certain wearing and abrasive properties the intensely hard white iron—usually chilled—is employed; usually this type is the more brittle but the hardest.

The strength, endurance, wearing, density, and expansion properties (in solidifying) are controlled primarily by the distribution of carbon in the states of graphite and cementite, this is effected chiefly by the amount of silicon, manganese, sulphur, and phosphorus present, and also by the rate of cooling.

Grades of Plain Cast Irons

Apart from the foundry or pig irons, the ordinary cast irons used for various kinds of commercial castings contain carbon in two forms, namely, (1) combined and (2) graphite, together with small amounts of other metals or elements such as manganese, silicon, phosphorus, and sulphur.

In the *combined state*, the carbon is present in the form of iron

carbide, or pearlite; the greater the proportion of combined carbon the more pearlitic does the structure become.

The *graphitic form* of the carbon is that of free minute flakes of graphite.

The respective proportions of combined and free graphite in cast iron are governed largely by the amount of silicon and certain other constituents present. When cast iron contains the greater proportion



FIG. 30 CAST IRON, SHOWING GRAPHITE AND WELL-LAMINATED PEARLITE. $\times 400$

of its carbon in the graphitic state it is termed grey cast iron, when the combined carbon predominates it is termed white cast iron. Intermediate grades are usually known as the mottled cast irons.

The structure of grey cast iron (Fig. 29) consists of graphite and pearlite in a silicon-ferrite matrix, the black lines of the graphite and grey patches of the pearlite showing up against the lighter silicon-ferrite matrix. Fig. 30 shows the structure of grey cast iron to a higher magnification than that of Fig. 29, the well-laminated pearlite and the graphite flakes are clearly shown.

In the case of the whiter cast irons (Fig. 31) there is of course a greater proportion of pearlite in the structure and a corresponding reduction in the graphite flakes, so that identification is facilitated.

In the metallurgical sense, cast iron includes the whole range of iron-carbon alloys having carbon in excess of that found in steels. The lower limit for pure iron-carbon alloys is at 1.7 per cent carbon, but it should be mentioned that so pronounced are the effects of certain other elements—particularly those of silicon and phosphorus—on the carbon content that it is not always possible to conclude from the carbon content alone whether the ferrous alloy is a cast iron or a steel.

It is for this reason that the microscopic method of examination is employed to decide such points.

The cast irons used in commerce usually contain from about 2.7 to 4.0 per cent (total) carbon. The grey cast irons, as cast, may contain up to 3.6 per cent carbon, of which about 0.6 to 0.9 is combined carbon and the remainder graphitic.

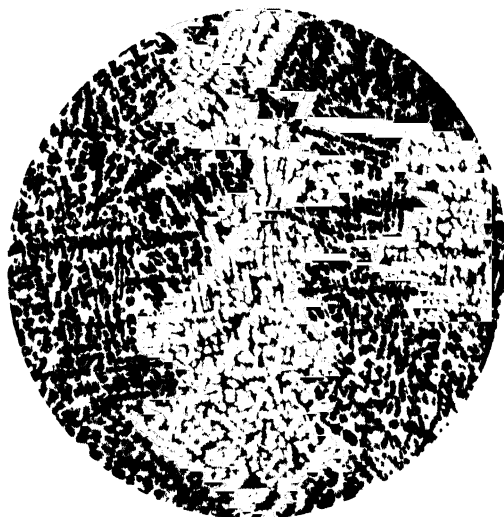


FIG. 31. WHITE CAST IRON. $\times 50$

The white areas show the cementite constituent.

The compositions of most commercial cast irons usually fall within the following percentage limits —

Iron	93 to 96 per cent
Carbon (total)	1.8 to 4.0 "
Phosphorus	0.05 to 1.0 "
Sulphur	0.05 to 0.12 "
Silicon	1.0 to 2.5 "
Manganese	0.4 to 1.2 "

The low-carbon phosphoric irons usually have from 1.8 to 1.9 per cent total carbon, with phosphorus up to 0.7 per cent.

Fig. 32 shows the constitution and properties of a series of cast irons containing a total of 4 per cent of carbon, but with this carbon changing progressively from the state of graphite to that of cementite, the corresponding qualities being summarized in Table 7.

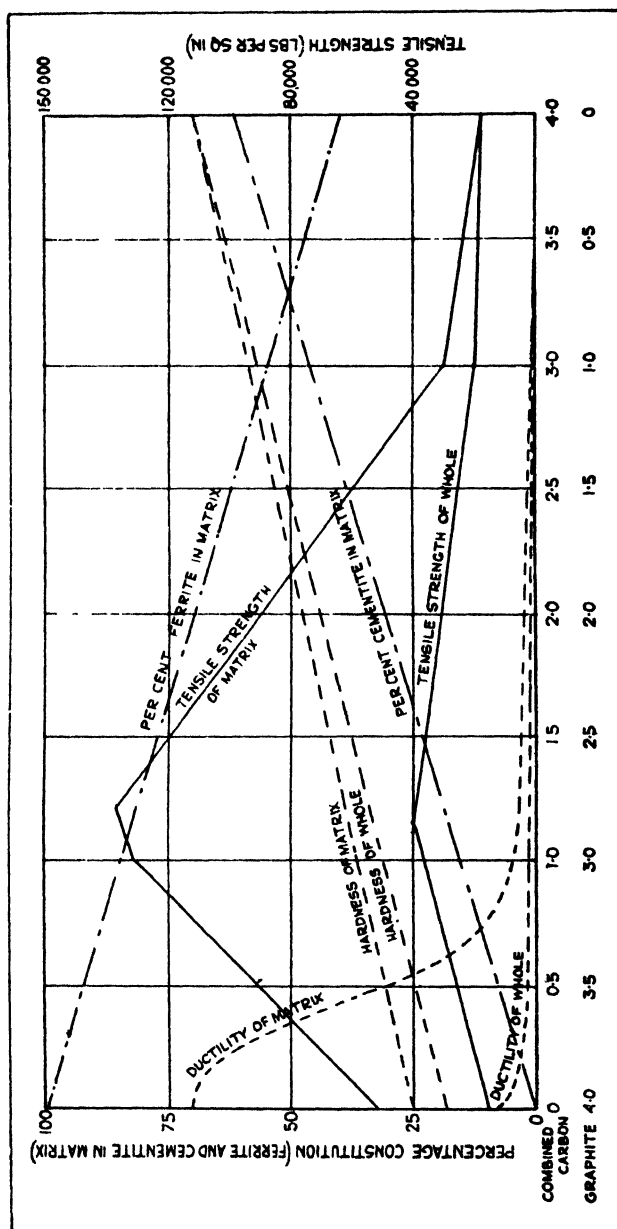


Fig. 32. SHOWING THE CONSTITUTION AND TEXTILE STRENGTHS OF DIFFERENT CAST IRONS

It will be evident from Fig. 32 and the table that as the graphite is replaced by combined carbon, or cementite, the hardness, brittleness, and density increase. It is also known that the expansion in solidification decreases under these circumstances. The maximum tensile strength appears to correspond with a combined carbon content of about 1.1 to 1.2 per cent.

TABLE 7
PROPERTIES OF PLAIN CAST IRONS

Combined carbon	0 to 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Graphitic carbon	3.5 to 4.5	3.0	2.5	2.0	1.5	1.0	0.5	0
Strength	Weak	Strongest					Weak	
Brittleness	Least brittle						Most brittle	
Hardness	Softest	Soft			Harder		Hardest	
Remarks	Greatest resistance to shock		Moderate resistance to shock		Will withstand little shock unless metal is supported			
	Best machinability but lowest abrasion resisting qualities		Moderate machinability and better abrasion resistance		Not readily machinable. Maximum abrasion resistance			

Grey Cast Iron

In general this grade, on account of the greater proportion of free to combined carbon, reveals a coarser and grayer structure than the whiter irons. It is, however, more fusible, less brittle, more readily machinable and "ductile" than the latter variety. On the other hand, grey cast iron is weaker in tension and compression, and has a lower hardness value.

In its commercial compositions, grey cast iron usually contains from 2.5 to 3.75 total carbon. It is much used for machinery castings and for machine frames and bases, more particularly those of intricate form. Owing to its good casting qualities, cheapness, and ease of machining this grade of iron has much to recommend it for such purposes.

In regard to its *wear resistance*, the particles of free graphite form a kind of lubricating element which tends to reduce the wear when in contact with other metal surfaces; in this respect it may be said to behave like a bearing metal, such as whitmetal bronze, in having a heterogeneous structure consisting of hard and soft constituents. Chilled grey cast iron has excellent wearing qualities.

The tensile strength of grey cast irons, as cast, varies from 8 to 14 tons per sq. in., according to the composition and mode of casting, etc.; it may, however, under favourable circumstances be as high as 20 tons per sq. in.

The compressive strength ranges from 40 to 60 tons per sq. in.

The modulus of elasticity lies between 6400 and 7500 tons per sq. in.*

The modulus of rigidity varies from 3000 to 3400 tons per sq. in.

The specific gravity of grey cast iron is from 6.9 to 7.3, the corresponding weights per cubic foot being 430 lb. and 445 lb. respectively.

White Cast Irons

These irons have a hard, close-grained structure, silvery white in fracture and possessing good wearing qualities, since they take a high degree of polish. White cast iron is more brittle, less fusible, and more difficult to machine than grey cast iron. Moreover, it does not take such good impressions from the moulds when cast.

The total amount of carbon usually lies between 2.8 and 3.5 per cent, of which from 0.6 to 0.8 per cent is in the combined form. When chill cast the skin sections contain from 0.8 to 1.4 per cent of combined carbon. When the combined carbon is between 0.8 and 1.0, the tensile strength is a maximum; above 1 per cent causes a reduction in the strength, which terminates only when the carbon is entirely in the form of carbide.

When the combined carbon exceeds about 0.8 per cent the metal is very difficult, if not impossible, to machine.

The tensile strength varies, according to the composition, mode of casting, and size of the casting, between 12 and 18 tons per sq. in.; compressive strengths usually lie between 40 and 80 tons per sq. in.

The longitudinal extension of cast iron varies from 0.000133 to 0.000156 in. per inch length per ton per square inch load.

The ordinary foundry test is to support a planed rectangular bar of 2 in. depth and 1 in. width at its ends, 3 ft. apart, and load it centrally; it should require between 25 and 32 cwt. to fracture it for a good-quality iron, from 10 to 20 cwt. for grey and weaker irons, and from 30 to 40 cwt. for the best grade.

Physical Properties of Plain Cast Irons

The specific gravity of white cast iron varies between 7.5 and 7.8; the corresponding weights per cubic foot are 467 lb. and 487 lb. respectively.

* Unwin

The melting-point of cast iron ranges from 1400° C. to 1500° C., according to the grade.

The specific heat at ordinary temperatures is 0.1298 for white cast iron and 0.1216 for the grey variety.*

The coefficient of thermal expansion of grey pearlitic irons† is about 1.4×10^{-5} taken over the range of 20° C. to the critical temperature of pearlitic change.

The electrical resistance of grey cast iron is about 60 to 100 microhms per c.c. and that of austenitic irons about 150.

The magnetic permeability of grey cast iron is about 240 and of austenitic irons only 1.03, as the latter are *practically non-magnetic*.

The thermal conductivity of cast iron (2 per cent C, 3 per cent Si, 1 per cent Mn) is 0.114 at 54° C. and 0.111 at 102° C.‡

General Classification of Cast Irons

Hitherto, only the more common grades of cast iron, which have long been in use for engineering purposes, have been considered. In recent years, however, as the result of a considerable amount of research, many new kinds of cast iron have been discovered so that it has become necessary to adopt a more general scheme of classification. The cast irons can be divided into three main groups, namely (1) *graphite-free, white or cementitic*, in which the carbon content is in the combined form; (2) *temper carbon graphite*, in which group are included the grey and machinable ferritic and pearlitic malleable irons; (3) *flake graphite*, characteristic of grey pig and grey cast irons.

Each of these main groups is capable of subdivision into other groups. Thus the graphite-free irons are subdivisible into the pearlitic and martensitic, whilst the flake-graphite irons can be subdivided into the ferritic, pearlitic, martensitic, and austenitic groups. Of these latter the pearlitic are by far the largest and most important in engineering application, as they include the bulk of the castings now made. This group of pearlitic flake-graphite irons is again divisible into several other sub-groups.

The method of classifying cast irons is that recommended by the British Standards Institution and is illustrated in Fig. 33.

In connection with the *ferritic irons*, in the normal cast condition none of the ordinary irons used for engineering purposes is entirely ferritic, as these irons would require higher proportions of graphitizing elements such as silicon than would be satisfactory for general use.

* *Kempe's Engineer's Year Book*.

† Report, High-duty Cast Iron Research Committee, Inst. Mech. Engrs., 1938-9.

‡ Callendar.

CAST IRONS

Flake graphite (grey and machinable) CLASS 1		Temper carbon graphite (grey and machinable) CLASS 2		Graphite free (white or cementitic) CLASS 3	
Ferritic class 10	Pearlitic class 11	Martensitic class 12	Austenitic class 13	Pearlitic class 30	Martensitic class 31
Grade C B.S.S. No 321, class 110	Grade A B.S.S. No 321, class 111	Grade 1 B.S.S. No 786, class 112	Grade 2 B.S.S. No 786, class 113	Grade 3 B.S.S. No 786, class 114	Grade 4 B.S.S. No 786, class 115
	Normal black heart B.S.S. No 310, 1927 class 200	Thin white heart B.S.S. No 309, 1927 class 201	Normal white heart B.S.S. No 309, 1927 class 210	Pictur frame malleable class 211	Special malleable class 212
	Ferritic— class 20			Pearlitic class 21	

FIG. 33

The ferritic irons are, however, made chiefly for heat- and acid-resisting purposes.

Irons with high chromium contents have a ferritic matrix, whilst cast irons used for engineering purposes can be made wholly ferritic by suitably annealing either pearlitic or white (cementitic) irons used for malleable iron castings. ✓

Most of the ordinary cast irons in the normal cast condition possess a mixed *ferritic-pearlitic* structure with flake graphite and usually have properties intermediate between those of the ferritic and pearlitic irons. Thus they are harder and stronger than the ferritic ones and not as hard or strong as the pearlitic irons.

The *pearlitic irons* have a pearlitic structure with flake graphite and are considered to be the best structural irons. The pearlite occurs in lamellar form, although some variation in the degree of refinement of the lamellae occurs according to local conditions, whilst occasionally the carbide is so finely divided that a sorbitic or troostitic structure is obtained.

Pearlitic irons can be *spheroidized* by special heat-treatment, so that the carbide occurs in the form of spherical inclusions in ferrite.

It has been found* that if a cast iron, all-pearlitic with about 0.7 per cent of carbon in the combined form, contains less than this amount of carbon, some ferrite is present. If more, some free cementite or carbide. The extent to which a cast iron can be hardened by the presence of carbide over that required for pearlite formation without sacrificing machinability is limited, but the combined carbon can be raised to 1.1 per cent or more without giving an unduly hard or unmachinable iron, and with improved mechanical properties. Malleable annealing of white cast iron can be arranged to give an all-pearlitic structure with temper carbon.

In regard to the hardness of the various structural groups of cast irons the following values have been established—

Structure	Ferritic	Ferritic-Pearlitic	Pearlitic	Austenitic	Martensitic	Cementitic or White
Brinell hardness	110-140	140-180	180-350	140-160†	350-450‡ (Soft)	280-550

* *Special-duty Cast Irons* (Austenitic and Martensitic Irons), Research Committee on High-duty Cast Irons for General Engineering Purposes Report, Inst. Mech. Engrs., 1941.

† 160-220 with chromium.

‡ The hard structure gives 550-700.

Effects of Various Elements

Apart from the carbon content, other elements, including silicon, phosphorus, sulphur, manganese, nickel, chromium, molybdenum, etc., have certain influences upon the physical and mechanical properties of cast iron. The general effects of these elements will now be considered.

✓ **Silicon.** The silicon content of cast iron may lie between 0.2 and 4.0 per cent, but usually ranges from 0.5 to 3.5 per cent. It is a constituent of all irons as silicide of iron dissolved in the iron or ferrite.

Silicon tends to promote the formation of graphitic iron and in general appears to render any cementite present unstable. It also tends to lower the melting-point.

When silicon is added to white cast iron, up to about 1 per cent, it decreases the chilling quality, but increases the strength of the iron. The greater strength occurs in irons having from 0.8 to 1.0 per cent combined carbon. Any further addition of silicon decreases the combined carbon and also lowers the strength.

When the silicon is in excess of about 3 per cent its effect upon the formation of graphite becomes negligible, and further increase up to 5 per cent tends to make the iron become white.

When more than 2 per cent of silicon is present it has a hardening effect upon the ferrite. Fig. 34 shows the effect of silicon on the strength of cast iron.

Increase in the silicon content has the effect of *reducing the shrinkage of the cast iron*. Thus, in the case of a series of square bars of 2-in. section* containing various percentages of silicon, from 1.0 to 3.5, the corresponding shrinkages, in inches per foot, decreased from 0.129 to 0.065.

The size of the square bar was also found to influence the shrinkage, for as the size increased from 0.5 in. (side) to 4.0 in., with 1 per cent silicon, the shrinkage per foot diminished from 0.178 to 0.102.

A similar reduction of shrinkage with increase of section was found in all the other cases over the range of silicon content stated.

A low silicon content is usually associated with cast irons which have to be hard and resist abrasive action. Thus *cast-iron brake shoes* usually contain from 0.5 to 0.8 per cent silicon. By varying the *rate of cooling* the cementite structure can be effectively controlled. Thus, rapidly cooled or "chilled" castings have more cementite, whilst slowly cooled ones are softer and more graphitic.

In the case of thick sections, such as *machinery castings*, the metal

* W. J. Keep, *Proc. Amer. Soc. Mech. Engrs.*, XVI.

must be softer than the hard white iron for machining purposes; it is usual to employ from 1.5 to 2.5 per cent silicon in such cases.

For *hydraulic and steam cylinders*, where a dense, hard structure is

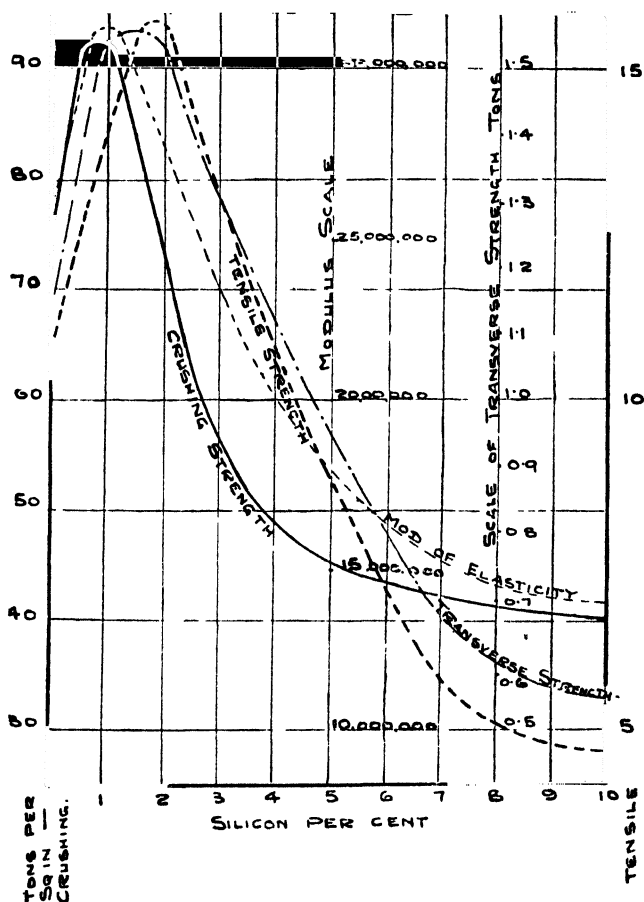


FIG. 34. VARIATIONS IN MECHANICAL PROPERTIES OF CAST IRON WITH INCREASING SILICON CONTENT

necessary, there must be a minimum of graphite, and the silicon content, therefore, is limited to 1.0 to 1.7 per cent.

Softer iron castings, and those for *thin ornamental work*, contain from 2.0 to 2.7 per cent silicon.

The proportions of silicon shown in Table 8 may be taken as a rough guide.

TABLE 8
PROPORTIONS OF SILICON FOR DIFFERENT PURPOSES

Part	Thin Pulleys	Medium-size Ordinary Castings	Large-size Ordinary Castings	Maximum Strength and Wearing Properties
Percentage of Silicon	2.3-2.8	2.0-2.5	1.5-2.0	0.8-1.2

Phosphorus. This element tends to give greater fluidity to the molten metal, increases the fusibility and reduces both the density and the shrinkage. Increasing the phosphorus content, however, results in increased brittleness, so that for castings subject to shock conditions it is usual to limit the phosphorus to 0.4 to 0.5 per cent with suitable carbon and silicon contents.*

The proportions of phosphorus given in Table 9 may be taken as a rough indication in the selection of cast iron for the purposes stated.

TABLE 9
PROPORTIONS OF PHOSPHORUS FOR DIFFERENT PURPOSES

Part	Ornamental Castings for Light Loads	Gas and Water Pipes	Pulleys (Medium)	Piston Rings I.C.	Auto mobile Cylinders	Steam Cylinders	Large Machinery Castings
Percentage of Phosphorus	1.0-1.6	0.8-1.2	0.6-0.8	0.7-1.0	0.4-0.7	0.2-0.5	0.5-0.6

The permissible phosphorus is reduced by the presence of much sulphur or manganese and by rapid cooling or "chilling", each factor leads to the formation of brittle cementite.

Sulphur. This constituent acts in an opposite manner to silicon, i.e. it tends to alter the constitution from graphitic to cementitic, causing hardness and brittleness; the latter effect is more marked at the higher solid temperatures and is known as "red shortness."

A sulphur content of 0.01 per cent is equivalent to 1.15 per cent of silicon in opposing the formation of graphite.

In practice the sulphur content is seldom allowed to exceed 0.1

See also "Phosphoric Cast Irons," p. 68.

per cent and in cast iron specifications for most engineering purposes it is kept down to a maximum of 0.05 to 0.08 per cent.

Manganese. This metal tends to oppose the formation of graphite and to lessen the unfavourable effects of sulphur, by promoting the less harmful manganese sulphide. It is usual to arrange for at least twice the quantity of manganese as sulphur in cast iron for this reason.

Manganese renders the iron harder but more brittle, strengthening the casting and refining the grain.

The usual proportions of manganese in good-quality high-strength plain cast irons range from 0.6 to 0.8 per cent. In acid-resistant irons it varies from 1.0 to 1.5 per cent; for chill castings it is usually from 0.3 to 0.6 per cent.

Nickel. The addition of small percentages, namely, 1.5 to 2.0, of nickel to cast iron has the effect of (1) reducing porosity, (2) refining the grain, (3) reducing and controlling chill, (4) increasing the strength and hardness without detracting from the machinability, and (5) producing uniform castings for complex or irregular shapes.

The effect of nickel, when the initial silicon content is high enough to give coarse graphite, is to make the graphite flakes smaller, i.e. to refine the grain. With high silicon contents, namely, of 3 per cent, the effect is less marked.

In regard to the effect of nickel in improving the mechanical properties of cast iron, Table 10* illustrates the beneficial effects of increasing amounts of nickel up to 2.0 per cent upon grey cast iron having 3.1 per cent of carbon and 2 per cent silicon.

Although nickel increases the hardness without changing the machinability in a similar manner to silicon, the latter element tends

TABLE 10
EFFECT OF NICKEL ON STRENGTH OF GREY CAST IRON

Nickel Per cent	Transverse Strength Tons per sq. in.	Tensile Strength Tons per sq. in.	Compressive Strength Tons per sq. in.
0	1.52	10.0	33.5
0.5	1.78	13.7	35.8
1.0	1.96	14.5	37.6
1.5	1.99	14.6	40.0
2.0	1.98	14.5	42.5

* "Nickel and Nickel-chromium in Cast Iron," T. H. Turner, *Foundry Trade Journal*, 1927-8.

to impair the physical qualities of the iron, for it secures machinability by graphitizing alone, so that the hardness is reduced. Nickel-hardening action is obtained by a progressive and uniform hardening of the iron matrix—producing sorbite—instead of by an increase of carbides. The process appears to be an increase in the strength of the pearlite grains by reducing their size and then a change to sorbite. The graphite is still present but is of smaller size and more uniform in character.

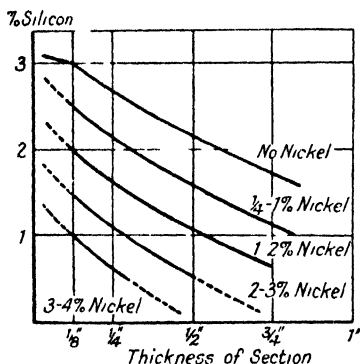


FIG. 35 SHOWING SILICON AND NICKEL PERCENTAGES FOR CASTINGS OF THIN SECTION HAVING GREY AND MACHINABLE QUALITIES. (TOTAL C 3.4 TO 3.6 PER CENT)

Fig. 35 illustrates the silicon and nickel percentages required to make castings of different thicknesses ($\frac{1}{8}$ in. to $\frac{3}{4}$ in.) completely grey and machinable.

Nickel also reduces chill in iron castings. Although silicon also exerts a similar effect on graphitization, there is an impairment of physical properties with progressive increase in the silicon content, giving more open grain, greater tendency to porosity and internal shrinkage, decreased hardness and strength. While nickel acts powerfully to reduce the combined carbon to the free carbide point (about 0.8 per cent) it acts only mildly beyond that point, and does not

enlarge the grain and soften the iron when present in excess. In the case of a cast iron containing 3.60 per cent carbon and 0.79 per cent silicon, progressive additions of nickel up to 5 per cent reduced the chill practically proportionately. Even 1 per cent of nickel had an appreciably beneficial effect in reducing chill.

Another important property conferred on cast iron is that of *uniformity of hardness* throughout light and heavy sections alike. Since nickel both reduces chill and hardens iron it is possible, using additions of 1 to 3 per cent, to harden the heavy section and at the same time to render the light section more machinable. In the case of relatively heavy sections with high-silicon irons, the use of up to 0.57 per cent of chromium is often advantageous.

Nickel has an important property in internal combustion and steam engine castings in giving an appreciably *higher wear resistance*, the wear of the metal being about one-half to one-fifth that of plain cast iron used for such castings. This is due chiefly to increased

hardness, finer structure, and absence of brittle carbide particles, which when dislodged by abrasion tend to score the sliding surfaces. Cast iron in which the matrix has been hardened up to 200 to 250 Brinell hardness by the use of nickel is free from such hard particles, takes a higher polish, and has much better wearing qualities.

Another beneficial effect of nickel is to neutralize the bad effects of unavoidable variations in the silicon content of cast iron. In the presence of 0.25 to 0.50 per cent nickel the silicon may vary from 1.25 to 1.55 per cent in the usual way without seriously affecting the good qualities of the iron.

Typical automobile cylinder block castings used for American engines contained 3.35 per cent total carbon; 0.6 per cent manganese; 0.08 per cent sulphur; 0.45 per cent chromium; 1.25 to 1.35 per cent nickel; and 2.20 per cent silicon.

In one particular instance a well-known mass-production car engine employed 2 per cent nickel with 1.7 per cent silicon, giving a Brinell hardness of 200 and an increased cylinder wearing life two and a half times as great as for the best plain cast irons previously used.

In addition to nickel and chromium, *molybdenum* is employed for producing close fracture grey cylinder irons having excellent wearing qualities. Further reference to the effect of this element is made later.

The percentage composition is usually within the following limits: Total carbon, 3.1-3.4; graphitic carbon, 2.5-2.8; combined carbon, 0.5-0.7; silicon, 1.8-2.4; manganese, 0.5-0.8; phosphorus, 0.12-0.20; sulphur, 0.10-0.12; chromium, 0.10-0.50; nickel, 0.25-1.50, molybdenum, 0.10-0.70.

The tensile strengths of these irons vary from 15.5 to 18.0 tons per sq. in.

In addition to automobile cylinder blocks, the irons in question are used for making *cylinder heads, brake drums, cylinder liners, clutch plates, and flywheels.*

Range of Nickel Cast-iron Alloys. For steam and Diesel engine castings, such as frames, cylinders, and heads, the addition of 0.5 to 2.0 per cent nickel under suitable conditions greatly improves the grain structure, hardness, and strength, giving pressure-tightness and increased resistance to wear and heat effects. Moreover, these irons are readily machined and exhibit uniformity both for thin and thick sections in the same casting.

Somewhat higher additions of nickel, namely, up to 6 per cent, are employed to provide a *martensitic structure*, so that although the castings are still grey, they are very hard and offer a high resistance to wear. Such irons are usually responsive to heat-treatment and yield

increased hardness and toughness. Additions of nickel above 15 per cent give the iron an *austenitic structure* whereby the castings possess a high degree of heat and corrosion resistance, whilst having other desirable physical properties to which reference will be made later.

Vanadium. This element in cast iron has a reverse effect to that of nickel, since it tends to maintain the carbon in the combined state, reducing the amount of graphite; the latter is rendered more uniform in size and in its distribution. Vanadium has a definite grain-refining influence and serves to produce soundness in castings. The structure of the iron is pearlitic, the lamellae being fine and closely packed in a homogeneous matrix.

The mechanical properties of vanadium iron are improved by the element in question without affecting the machinability of the metal.

The iron has a fine-grained structure of very good wear resistance and able to take a high degree of polish. The wear-resistance properties are believed to be due to the effect of the vanadium upon the cementite, its prevention of ferrite-graphitic soft spots, and absence of dendritic structures.

A further advantage of vanadium cast iron is *the reduction of growth* and distortion after repeated heating from above the transformation range of the matrix. The iron can also be heat-treated to give improved qualities; part of the stresses due to quenching are relieved by tempering. There is only slight reduction in strength when the metal is tempered.

The percentage composition limits of plain vanadium irons are as follows: Total carbon, 3.2-3.7; combined carbon, 0.6-0.8; graphitic carbon, 2.5-2.7; silicon, 1.3-2.5; phosphorus, 0.2-0.5; sulphur, 0.07-0.10; manganese, 0.5-0.7; vanadium, 0.10-0.25.

Vanadium is also employed for special iron castings in association with small percentages of nickel, chromium, copper, molybdenum, or titanium; in all instances, however, the percentage of vanadium lies between 0.10 and 0.25.

A typical percentage composition for an *automobile engine cylinder block* of hard wearing properties combined with adequate tensile strength is as follows: Total carbon, 2.85; combined carbon, 0.50; graphitic carbon, 2.35; silicon, 1.70; phosphorus, 0.30; sulphur, 0.10; manganese, 0.40; nickel, 0.85; vanadium, 0.10.

Chromium. The effect of chromium in cast iron is to increase the combined carbon and improve both the tensile and compressive strengths, as well as the hardness; it is possible to select the percentage of chromium so as to regulate, within limits, the proportion of combined carbon. Usually, however, chromium is used in modern cast irons in

association with nickel, and sometimes molybdenum, the chromium being about one-quarter to one-third of the nickel content.

The addition of chromium to cast iron containing nickel has the effect of stabilizing the carbide and opposing the formation of graphite caused by the presence of the nickel. The stable carbides of chromium are formed from the excess carbon, so that instead of having a *pearlite-graphite* structure the iron is given one of *pearlite-cementite* or *martensite-cementite*.

It is undesirable to use excessive amounts of chromium since these tend to produce hard areas of chromium carbide in the iron, which are so hard that the castings are often unmachinable. It is usual, therefore, to employ nickel alone or nickel with chromium of about 25 to 30 per cent of the nickel content. Usually not more than 0.5 per cent chromium is employed in nickel-chromium alloy irons.

For *chill castings* about 4 per cent nickel and 1.5 per cent of chromium with 3 per cent carbon give very good results, the chill being deep and of a martensite-cementite structure.

High-duty Cast Irons

The plain grey and white cast irons, whilst suitable for a large number of commercial applications, are not now employed for many engineering purposes on account of their relatively low strength properties, inability to withstand heat and corrosion effects, brittleness, and low wear-resistance qualities, etc.

A number of special cast irons, some of which have already been mentioned, have been introduced having additional constituents to the carbon, silicon, manganese, sulphur, and phosphorus, namely, nickel, chromium, molybdenum, vanadium, copper, etc., whereby the irons are given special properties to meet the particular conditions relating to corrosion, heat, erosion or wear, magnetic properties, etc., where mechanical requirements are not of primary importance. These high-duty cast irons were first included in the British Standard Specification No. 786, in 1938, covering three grades of iron for special purposes. Special foundry methods are used in the production of these irons, and it may be noted that, whilst most cast irons are produced in the cupola furnace, different types of furnace are employed for making high-duty irons. These include the air, rotary, and electric furnaces; the latter are of the indirect and also the direct arc patterns.

The influences of nickel and chromium on cast iron have previously been considered.

Molybdenum. Small percentages up to about 0.4 per cent, usually in addition to the low nickel and chromium content before-mentioned, toughen and improve the strength of the iron to a somewhat marked

extent. The element has a dual action in exerting a slight hardening action by stabilizing the iron carbide and by toughening the matrix. It also promotes a more uniform distribution of the graphite and appears to reduce the size of the graphite particles. It retards the grain growth and is particularly applicable to castings of intricate form, giving homogeneity to both thick and thin sections.

The tensile strength is increased with the molybdenum content up to 1.5 per cent; the effect of the latter percentage of the element on a plain iron having a tensile strength of 11 tons per sq. in. is to increase this to 19 tons per sq. in.* The transverse strength is increased in a similar manner. Thus with 1.5 per cent addition of molybdenum to a plain cast iron the transverse breaking load on round bars of 1.22 in. diameter at 13 in. long, placed on 12-in. support knife edges, was increased from 1.40 tons for the plain iron to 2.20 tons.

In regard to the hardness, the addition of 0.3 per cent molybdenum increases the hardness and the latter increases with further additions up to 1.5 per cent, above which amount the metal becomes difficult to machine. Molybdenum-iron castings containing nickel and chromium are used for automobile cylinder blocks where a hard wearing surface is required. Machining is easier and in general sounder castings are obtained. Other applications include castings for heavy machine tools where resistance to wear and strength without unnecessary weight are required; also for pipes, ingot moulds, pressure castings, and general high-duty engineering purposes.

Chilled-iron rolls for steel rolling mills, and for rolls employed for brass, bronze, copper, and even for paper, are often made from molybdenum iron, a typical composition being as follows: C, 2.96 per cent; Mn, 0.27 per cent; P, 0.34 per cent; S, 0.06 per cent; Si, 0.60 per cent; and Mo, 0.25 per cent.

It is usual, however, to limit the carbon to 3.0–3.75 per cent; the manganese to 0.25–0.50 per cent; the silicon to 0.75–1.75 per cent; the molybdenum to 0.25–0.50 per cent, and to employ from 0.80 to 1.50 per cent chromium; the sulphur and phosphorus should be as low as possible.

A molybdenum cast iron† having a tensile strength of 22 tons per sq. in., transverse strength of 1.9 tons with deflection of 0.124 in. and Brinell hardness of 228 had the following composition: Total C, 3.21 per cent; combined C, 0.7 per cent; Mn, 0.63 per cent; P, 0.272 per cent; S, 0.098 per cent; Si, 2.00 per cent; Mo, 0.37 per cent; and Cr, 0.19 per cent; there was no nickel present.

* *Molybdenum in Cast Iron*, Molybdenum Corporation of America Researches.

† *Ibid*, page 66.

Copper. This more recent metal addition to cast iron* has a mildly graphitizing action and it toughens the matrix. Its solubility in cast iron is, however, limited, but subject to this its action is not unlike that of nickel when employed in small proportions. These properties render copper a useful addition to automobile cylinder or pressure castings since it prevents the light sections from chilling and gives a close structure in the thicker parts. Where used to replace part of the silicon content, copper gives a marked increase in the mechanical properties of cast iron, promotes uniformity of structure, and "damps" out the effects of small changes of composition. Another important effect is to balance the chilling influence of the hardening constituents such as manganese, chromium, and molybdenum commonly used in high-duty cast irons, which otherwise might render the iron brittle and difficult to machine.

Copper, in association with nickel and chromium, produces cast irons notable for their resistance to the effects of corrosion and high temperatures. On account of their resistance to attack by comparatively strong acids, caustic liquors, and organic acids these irons have important applications in the chemical industry. They also show a marked *resistance to growth* effects, due to their austenitic structure; they are non-magnetic and have a high electrical resistance.

About 7 per cent of copper is generally used in these irons. Complete graphite refinement is obtained by means of high copper additions (6 to 8 per cent) to ordinary grey irons.

TABLE II
HIGH-DUTY CAST IRONS CONTAINING COPPER

C	Si	Mn	Cu	Cr	Mo	Ni	Tensile Strength Tons per sq. in.	Brinell Hardness
2.62	1.90	0.84	1.58	--		0.64	22.1	264
3.22	2.10	0.62	0.43	0.57	--		23.1	360
2.99	2.25	0.61	1.66	--	0.51		21.0	255
2.92	1.61	0.64	1.23	--	0.47		26.1	259
3.06	1.90	0.85	1.51	--		0.50	19.6	240
2.85	1.61	0.53	1.90	--			27.8	299

The S and P contents below 0.1 and 0.4 in all cases.

* *Copper in Cast Steel and Iron*, Copper Development Association, London, 1939.

Phosphoric Cast Irons

More recently, as the result of research work,* a class of *high-duty phosphoric cast irons* has been introduced; typical irons of this class containing 0.75 to 0.85 per cent of phosphorus give tensile strengths of about 18 tons per sq. in. Hitherto, it had been the practice in the automobile and other engineering industries to limit the percentage of phosphorus to a low value in order to produce dense and strong castings. It has since been shown that large castings can be made to yield a dense structure free from shrinkage troubles in spite of a higher phosphorus content provided their silicon and carbon contents are suitably lowered.

The structure of ordinary cast iron consists of a matrix of pearlite, or pearlite and ferrite, broken up by graphite flakes. If phosphorus is present in the iron, another structural constituent appears, a microscopically fine conglomerate into one of the two parts of which the phosphorus enters. This constituent, for which the presence of phosphorus in the iron is wholly responsible, is a binary eutectic obtained from what was at solidification a ternary eutectic of γ -iron, iron carbide, and iron phosphide. This loses practically all of the carbon during the cooling process, the carbide decomposing to iron and graphite, so that as observed under the microscope it is an intimate mixture of iron and iron phosphide. The iron phosphide is hard and brittle, and confers these properties to some extent on the conglomerate into which it enters. By controlling the composition of a phosphoric iron, it is possible so to direct the solidification of the phosphide eutectic—which is the last constituent of the melt to solidify—that the most beneficial or least harmful distribution of phosphide results. The phosphide compound is then distributed as a network or honeycomb throughout the matrix.

Phosphorus, like silicon, lowers the capacity of the melt to hold carbon in solution at solidification, so the carbon content of a phosphoric iron made from normal materials is lower than that of an otherwise similar non-phosphoric iron. As the phosphide eutectic melts at a lower temperature than the remainder of the metal, phosphoric irons solidify over a wider range of temperature than the non-phosphoric irons. This aids the foundry process and assists castings to take a sharp impression of the mould, but it also sets up conditions which may create difficulties resulting in shrinkage defects.

In the Report referred to in the footnote below, a table is given showing the composition limits for the phosphorus, silicon, and

* *Phosphoric High-duty Irons*, Second Report of Research Committee on High-duty Cast Irons for Engineering Purposes. Inst. Mech. Engrs., 1941.

carbon that will produce grey phosphoric cast irons of adequate strength and soundness. It is shown that when the silicon is below 1.5 per cent an iron with a phosphorus content of 1.2 per cent should have a maximum percentage of total carbon of 3.3. Further, for a maximum silicon and phosphorus content of 3.0 and 1.2 per cent respectively, the total carbon must not exceed 2.7 per cent. Small thin castings poured in the ordinary way require relatively high silicon and carbon contents to ensure a grey structure; and to ensure soundness the phosphorus must be kept low. In larger castings, where lower silicon and carbon contents can be used, the phosphorus can be increased.

In regard to the effect of variation of phosphorus on the mechanical properties of cast iron, whilst it is not practicable to give figures of general application since the properties of a given iron depend upon many other factors than the phosphorus content, it may be stated as an indication of the magnitude of the change that the ultimate tensile stress may be expected to improve about 2.5 per cent for each 0.1 per cent of phosphorus added to a non-phosphoric iron, up to a maximum of 0.35 per cent phosphorus, and then to diminish at a similar rate. The ultimate transverse stress is usually slightly more erratic, and the change is rather less pronounced—about 2.4 per cent higher for each 0.1 per cent of phosphorus added, up to the same maximum, followed by diminution at the same rate. The change in transverse deflection is of the order of 2.4 per cent, the variation occurring in a similar way.

The influence of phosphorus on elastic modulus is not pronounced. The fatigue strength may be expected to follow the tensile strength.

The Brinell hardness number of plain cast iron increases uniformly with increase in phosphorus content, and a rise of about 4 points may be expected for each 0.1 per cent phosphorus added to a non-phosphoric iron. Increased Brinell hardness normally indicates decreased machinability.

Impact or shock strength diminishes with increase in phosphorus content, and the shock strength of a phosphorus-free iron may be expected to be reduced by about 5 per cent for each 0.1 per cent of phosphorus added.

Phosphoric cast irons can be produced to conform to the requirements of the British Standard Specifications Nos. 321 (1938) and 786 (1938) in regard to strength properties.

Low-carbon Alloy Cast Irons

When the amount of carbon is kept low in irons cast in the white condition and other elements such as nickel, chromium, or molybdenum

are employed, the iron can, by proper heat-treatment, be made to yield a fine structure in which the amount of graphite present is in the temper carbon form. A typical material* of this class, used for the crankshaft of a heavy oil engine, gave a tensile strength in the

heat-treated state of 63.2 tons per sq. in. with 1.0 per cent elongation and a Brinell hardness of 375. Its percentage composition was as follows: Total C, 1.74; Si, 0.62; Mn, 0.63, S, 0.05, P, 0.05; Ni, 1.94; Mo, 0.64. The metal was tempered, after heating to 1000° C. and cooling in air, for three hours at 550° C. and cooled in air.



FIG 36 "NOMAG" NON MAGNETIC CAST IRON, SHOWING STRUCTURE CONSISTING OF AUSTENITIC GRAINS SURROUNDED BY CEMENTITE BOUNDARIES, TOGETHER WITH GRAPHITE $\times 660$

Austenitic Cast Irons

This important group of irons includes those containing elements such as nickel, copper, chromium, with silicon and manganese. They bear a relation to ordinary cast irons similar to that which certain stainless steels bear to ordinary steels

Austenitic irons, although more expensive to produce, possess certain marked properties which

distinguish them from ordinary cast irons. They are of medium tensile strength combined with softness and ductility, have a high impact value, very good resistance to wear, erosion, corrosion and heat, are non-magnetic, have high thermal expansion coefficients, high electrical resistance, and low thermal conductivity. Owing to their relative softness these irons are easy to machine; they can also be welded satisfactorily.

Austenitic irons are not susceptible to heat-treatment, such as quenching and tempering, but can be annealed at low temperatures with advantage. These irons can be cast white if required; a simple heat-treatment such as annealing at 950° C. for thirty minutes gives an iron with 2 to 3 per cent elongation.

Austenitic irons, whilst more difficult to cast, can be made in the form of large or small castings (down to $\frac{1}{8}$ in. sections).

* "First Report on High-duty Cast Irons," Inst. Mech. Engrs., 16th December, 1938.

The melting-point is about 1150° C. and specific gravity 7.2 to 7.6.

Typical austenitic irons are "Nomag," "Ni-Resist" and "Nicrosilal," to which more detailed reference is made later.*

In connection with the formation of austenitic cast iron it may be noted that, in cooling cast iron, pearlite is formed at about 740° C. from the austenite deposited on solidification. This temperature of transformation can, however, be suppressed by the additions in sufficient quantity of certain elements; the temperature of formation of the pearlite can thus be reduced to below air temperature, so that in the cold state the iron has the structural character of austenite. In this connection about 20 per cent of nickel will produce an austenitic grey cast iron, but a part of this nickel may be replaced by smaller amounts of other elements such as *manganese* or *chromium*, provided that the additions of these are limited below the amounts causing the formation of excess carbides. *Copper* can also be employed, the ratio of nickel to copper being about 2 : 1.

It should be mentioned that when *manganese* is used with nickel in these irons about one part of the former is roughly equivalent to two parts of the latter, the practical limit of manganese being about 5 per cent.

Chromium, up to about 5 or 6 per cent, may be employed, with beneficial effects on strength, corrosion- and heat-resistance.

It is sometimes desirable to increase the proportions of the elements considerably above the limits mentioned as, for example, in the case of *special corrosion-resistant cast iron* containing up to 40 per cent nickel with 15 per cent of chromium.

Some typical austenitic irons will now be described in brief.

Nomag. This iron, developed in collaboration with Messrs. Ferranti Ltd., was produced by the addition of relatively large amounts of nickel and manganese in an ordinary mixture, giving a metal having the appearance and some of the properties of ordinary cast iron.

Nomag is employed chiefly on account of its non-magnetic properties for castings used in electrical engineering work, such as alternator coil supports, busbar chambers, alternator end rings and plates, oil switch covers, resistance grids, cable clamps and supports, transformer covers, etc.

It has a tensile strength of about 9 to 11 tons per sq. in. and a transverse strength on a 1 × 1 in. square bar with 12 in. centres of 24 cwt., as compared with 21 cwt. for ordinary grey cast iron. It is also superior in toughness, the Izod impact test value in ft.-lb. (for

* *Vide* also "Report on Austenitic Cast Irons," High-duty Cast Irons Research Committee, Inst. Mech. Engrs., 1941.

20 x 20 75 mm test piece) being 29 as compared with 11 for grey cast iron

It can be cast readily into complex shapes with ordinary foundry

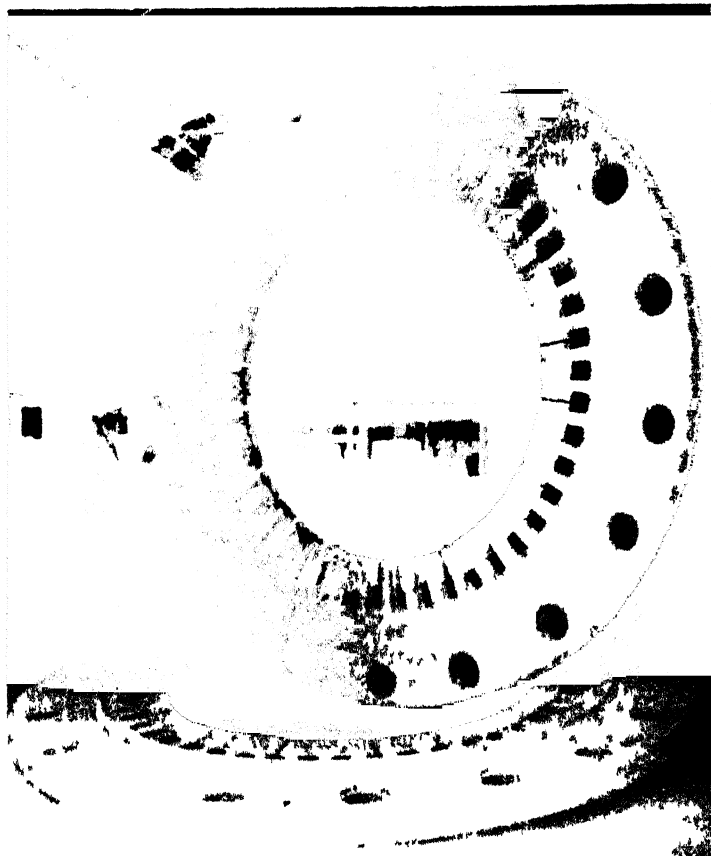


FIG. 37. STEEL END-RING CASTINGS IN NOMAG (NON-MAGNETIC CAST IRON) — WEIGHT $3\frac{1}{2}$ TONS EACH
(Messrs. Ferranti Ltd.)

equipment and has a shrinkage of $\frac{1}{8}$ in. per ft. (for ordinary grey iron this is $\frac{1}{16}$ in.)

Nomag can be machined readily, but owing to its toughness it is advisable to use the same kind of tools as for mild steel.

Nomag has a maximum magnetic permeability of 1.03 (cast iron, 240); specific resistance, 150 microhms per c.c. (cast iron, 95); temperature resistance coefficient, 0.00045, between 0 C. and 100 C., per degree C. (cast iron, 0.0019); coefficient of linear expansion, 11.9×10^{-6} per degree C. (cast iron 10.6×10^{-6}), and specific gravity, 7.2—which is the same as for grey cast iron.

Ni-Resist. This is an austenitic iron developed for corrosion- and heat-resistance. It has the following percentage range of composition: C, 2.6-3.2; Si, 1.2-1.5; Mn, 0.8-1.0; S, 0.12-0.10; P, 0.2-0.40; Ni, 13.0-16.0; Cu, 6.0-8.0; Cr, 2.0-6.0.

This metal is greatly superior to ordinary cast iron in resistance to corrosion attack by most acids and other corrosive mediums. Thus

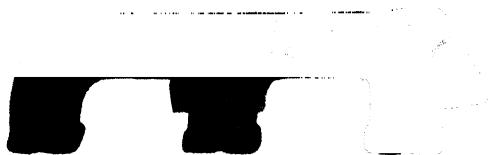


FIG. 38. AUTOMOBILE ENGINE EXHAUST MANIFOLD IN "Ni-Resist"
(CAST IRON)

the relative losses of weight per unit area per unit of time of Ni-Resist and ordinary cast iron under the action of 20 per cent hydrochloric acid were 62 and 11,180 respectively, for 20 per cent sulphuric acid, 41.8 and 13,720, and 20 per cent nitric acid, 7,830 and 10,092 respectively. For sea water, the relative figures were 6.2 and 23.2 respectively.

Ni-Resist has also excellent heat-resisting properties, not only on account of the resistance to oxidation of the matrix, but also because the amount of combined carbon normally found in the metal is low and no structural change takes place on heating; it retains its mechanical strength properties at high temperatures to a considerably higher degree than ordinary cast irons.

The tensile strength ranges from 13 to 17 tons per sq. in., with 1 to 3 per cent elongation. The elastic modulus is 16 to 19×10^6 lb. per sq. in. The transverse modulus is 22 tons per sq. in. The Brinell hardness varies from 140 to 200. The Izod impact resistance, for a 1.25 in. diameter bar (modified Izod test), is 52 ft.-lb. at room temperature. The metal is non-magnetic and has a high electrical resistance, namely, 135 to 140 microhms per c.c.

Ni-Resist is extensively used for castings liable to high-temperature exposure conditions. Typical instances of the use of this metal include

burner parts, superheater tube spacers and hangers, soot-blower nozzles, Diesel engine heads, combustion chambers, throats and flame plates on light alloy pistons, furnace doors and grates. This iron has

also been used with satisfactory results for valves and valve seatings of internal combustion engines.

Nicrosilal. This is another more recent heat-resisting cast iron* containing about 18 per cent nickel; 6 per cent silicon, 1·8 per cent (total) carbon; and 1 per cent manganese. The composition given is for a "soft" Nicrosilal iron. Where a harder and more resistant alloy is required the chromium content is increased up to 3 per cent; the composition can thus be varied to suit requirements. It is exceptionally resistant to growth† and scaling and is also very ductile for a cast iron. In consequence it is not liable to the cracking on sudden heating and cooling experienced with certain other alloy cast irons, such as the 5 to 6 per cent silicon iron "Sisal." It has a higher silicon content than Ni-Resist. It can be run into sections less than $\frac{1}{4}$ in. thick, and such sections



FIG. 39 ALUMINIUM "Y" ALLOY DIESEL ENGINE PISTON, FRIEDEL WITH CAST IN "NI-RESIST" INSERTS FOR THE PISTON RINGS
(Moxon Specialfluid Ltd.)

can be cast free from white or mottled iron. It is easy to machine and will give a fine surface finish which can be burnished.

Nicrosilal has an electrical resistivity of about 160 microhms per c.c.

The iron has a tensile strength of about 16 tons per sq. in. with 3 per cent elongation on a 2 in. gauge length. In the transverse bending test it gives about six times the deflection figure of ordinary cast iron under similar conditions. The Brinell hardness of the soft grade is about 110, whilst with the harder grades containing higher proportions of chromium the hardness value increases to 200 to 250.

As this iron is austenitic its thermal coefficient of expansion is higher than for normal grey irons, averaging $1\cdot8 \times 10^{-5}$ as compared

* *Nickel-chromium-silicon Cast Irons*, A. L. Norbury and E. Morgan, Iron and Steel Institute, September, 1932.

† See page 87.

with 1.4×10^{-5} for pearlitic irons. It is practically non-magnetic and has a low thermal conductivity, this being of the order of 0.083 as compared with 0.110 to 0.137 for grey cast irons.

Deflection tests made by the British Cast Iron Research Association at high temperatures showed that Nicrosilal retains its good mechanical properties at high temperatures to a greater extent than ordinary cast irons. For example, a good-quality engineering cast iron containing 3.1 per cent total carbon and 2.0 per cent silicon showed a deflection of 0.9 in. after six days at 850° C., while a Nicrosilal test piece had a deflection of only 0.08 in. under exactly similar conditions.

Nicrosilal is employed for furnace parts, special ingot moulds and bottle moulds, superheater castings, furnace grids, annealing pots, and numerous other applications where a high resistance to oxidation and growth and high resistance to temperature effects are required. It is interesting to note that this metal can be surface hardened, the hardness on the Brinell scale being about 450.

*Nimol.** This is another heat- and corrosion-resistant cast iron containing about 75 per cent of ordinary cast iron, 4 per cent chromium, and the balance Monel metal. It is harder and wears better than brass and can be used in place of the latter. It is stronger and tougher than cast iron and withstands the destructive effects of temperatures up to 600 C. and does not suffer from growth at these temperatures; intricate castings may be made of Nimol as readily as with cast iron.

It has a tensile strength of 9 to 12 tons per sq. in. with about 2 per cent elongation. The Brinell hardness is 200 (minimum). The specific gravity is 7.686. The shrinkage allowance for patterns is $\frac{1}{2}$ in. per ft. The electrical resistivity is 94.77 microhms per c.c. and permeability 1.4.

Nimol may be used at red heats over long periods without the disadvantages of ordinary cast iron. Thus, a sample of specially good-quality cast iron after thirty days at 600° C. was found to have lost 37 per cent of its strength and had increased in volume by 5 per cent. Nimol, under the same conditions, actually showed an increase in tensile strength of 3 per cent, although its volume had decreased by 0.4 per cent, so that temperature effects up to 600° C. may be considered to be negligible for all practical purposes.

It may be used at temperatures up to 850° C. for industrial purposes. Nimol is also strongly resistant to corrosion by acids. Thus, in the case of tests made with 5 per cent sulphuric acid the loss in weight of Nimol was only 1 per cent of that of cast iron during the same period.

* Ni-Resist has now replaced this alloy cast iron.

Inoculated Cast Iron

If, instead of adding the silicon with the pig iron and scrap when making cast iron, it is crushed and introduced to the molten metal, a marked improvement in the quality of the iron is produced and the product is termed "inoculated iron." The method mentioned gives plain irons of higher tensile strength and also avoids white or mottled regions in the irons, which in practice are near the margin on account of low carbon or silicon contents. The inoculation process enables irons to be made of lower carbon and silicon contents without being too hard, and thus gives higher tensile strengths; it is based upon the principle of adding a graphitizing element to an iron which would normally be white or mottled.

The structure of such irons is fully pearlitic with relatively fine flakes of graphite. Examples of special irons made by this process are the Meehanite and Ni-Tensyl. These irons are used for various engineering castings where high stresses occur or where reduced sections are required and ductility is not essential; these special irons give uniform properties in varying sections.

Meehanite Cast Iron. Originated in the U.S.A., the Meehanite process gives a low-carbon iron, rendered grey, from a white or mottled iron by the addition of a carbon-free silicide, e.g. calcium silicide.

A typical percentage analysis is as follows: Total C, 2.0 to 2.13; combined C, 0.72 to 0.99; Si, 1.35 to 1.39; Mn, 0.87 to 1.05; S, 0.04; P, 0.15 to 0.16.

Such irons give a tensile strength of 20 to 23 tons per sq. in. and Brinell hardness up to 500 in the highest grades.

Tests* made from separately cast bars of 1.2 in. diameter, machined to 0.798 in. diameter, gave a mean modulus of rupture of 39.7 tons per sq. in. and deflection of 0.32 in.; another specimen machined to a diameter of 0.564 in. from bars of 0.875 in. diameter gave a modulus of rupture of 42.8 tons per sq. in. and deflection of 0.15 in., with average tensile strength of 16.6 tons per sq. in.

Fig. 40 shows the structure of iron made by the Meehanite process, the section being etched with picric acid; the dark regions show the relatively small graphite flakes. Examples of tests made to demonstrate the ductility of piston rings made by this process are shown in Fig. 41.

There are five process Meehanite irons, designated A, B, C, D, and E respectively, giving a range of mechanical properties and wear, heat and corrosion resistances. The mechanical properties of these irons are given in Table 12.

* "Recent Developments in Cast Iron," J. G. Pearce, *The Metallurgist*, February-March, 1928.



FIG 40 STRUCTURE OF MEPHANE IRON. ETCHED
WITH PICRIC ACID 200



FIG 41 RESULTS OF TESTS ON MEPHANE IRON RODS
AND PISTON RINGS

- A White iron rod twisted 360° at 70° F.
- B White iron rod annealed at 70° F. and twisted lower end ham-
- C White iron rod annealed and knotted hot
- D Green iron rod annealed and coiled hot
- E Green iron rod annealed and distorted cold, the ring was

bent and for several times before it broke

TABLE 12
PROPERTIES OF MEEHANITE IRONS*

Meehanite	Tensile Strength (tons per sq. in.)	Transverse Strength (lb.)	Deflection (in.)	Brinell Hardness	Fatigue Strength (lb. per sq. in.)	Minimum Section for Small Castings (in.)
A	22.4 33.1	5500	0.16 0.20	196-500 600†	9.8 12.5†	0.375
B	20.0 26.8†	5000	0.18	196-450 500†	8.5 10.5†	0.25
C	17.8	4500	0.17	196-450	7.8	0.19
D	15.6	4000	0.17	175-450	6.7	0.125
E	13.4	3800	0.15	140-450	6.1	Any size

Meehanite irons machine in a similar manner to grey cast iron, but are free from white edges and hard spots.



FIG. 42 SMALL AIR-COOLED PETROL ENGINE CYLINDER IN NI-TENSYL
(Messrs. S. Russell Ltd.)

Ni-Tensyl Iron. This special process cast iron is characterized by its high strength and hardness, although it can be machined without difficulty. The table given below shows the percentage compositions for the plain and heat-treated irons.

The tensile strengths of the plain and heat-treated irons are 25 and 30 tons per sq. in. respectively. The Brinell hardnesses are 230 and 400 (as cast) respectively.

In regard to the heat-treatment process the metal is heated to 850° C. and quenched in oil, after which it is reheated to 350° C. and quenched.

Ni-Tensyl iron is used for all

	Total C	Si	Ni	Mn	P	S
Ni-Tensyl (plain)	2.7-2.9	1.25-1.75	1.25-1.75	0.5-1.0	0.3	0.12 (max.)
Ni-Tensyl (heat-treated)	2.7-2.9	1.25-1.75	2.5-3.5	0.5-1.0	0.3	0.12 (max.)

* Meehanite Metal Corporation, U.S.A.

† Heat-treated.

purposes where a high tensile strength combined with reasonable hardness and machinability are required; the heat-treatable grade is machinable as cast. The plain grade mentioned is especially suited to the manufacture of large press dies for drop forging, stamping, etc., whilst the heat-treated iron is employed for light blanking dies and small press dies.



FIG. 43 EMMEL THYSSSEN PROCESS CAST IRON. PICRIC ACID LICHED.
THE GRAPHITE IS PRESENT IN FINELY CURVED FORM. 200

Emmel Iron

This special cast iron, produced at the Thyssen works, Germany, is based upon the use of an iron with a carbon content of 2.2 to 2.8 per cent and a silicon one of 2.3 to 2.6 per cent, the metal being cast at a higher temperature than usual and poured from the cupola into dry sand moulds. The phosphorus content is maintained between 0.1 and 0.2 per cent.

Steel and wrought-iron scrap are used in making the iron. The structure of this iron is shown in Fig. 43.

In regard to the strength of the Emmel iron, a bar of metal cast to 1.2 in. diameter and machined to 0.564 in. diameter gave a tensile strength of 20.8 tons per sq. in. The percentage composition of the metal was as follows: Total C, 2.53; combined C, 0.71, silicon, 2.53.

Lanz Iron

This is another special high-tensile cast iron used for cylinder barrels and liners, etc. It has a low silicon content and is made by a method which controls the rate of cooling during the casting process, in order to obtain a pearlitic structure; the resulting metal shows pearlite with fine graphite flakes, uniformly dispersed. An average percentage composition is as follows: Total C, 3.0; Si, 0.9; P, 0.35; Mn, 0.7.



FIG. 44. LANZ PROCESS CAST IRON, SHOWING GRAPHITE AND PEARLITE
- 500

Piwowarsky Process Iron

This method of producing a heat-treatable cast iron employs an iron having a nickel and chromium content, the molten metal being subject to higher temperatures than usual; after casting, the metal is subjected to a special heat-treatment in order to develop its high strength properties. In this connection,* tensile strengths up to 47 tons per sq. in. have been obtained.

The principle of the method is first to produce an iron having the primary graphite finely divided and then to heat-treat the iron so as to produce a matrix of sorbitic pearlite. The carbon and silicon content of the iron is adjusted so that the iron would solidify in the moulds in the white or mottled condition. The amount of silicon is kept low to avoid ferrite formation during cooling. The iron is subjected

* *The Metallurgist*, January, 1926, and August, 1927.



FIG 45 ORDINARY CAST IRON MADE BY
PIWOWARSKI PROCESS, SHOWING (GRAPHITE)
STRUCTURE 500



FIG 46 STRUCTURE OF HEAT TREATED
PIWOWARSKI CAST IRON / 500

to an "annealing" process to complete the graphite formation by the splitting up of the hyper-eutectic cementite. The annealing of the primary graphite is carried out in a muffle furnace at 925°C . to 950°C . As soon as the castings attain this temperature the heat is shut off and they cool down slowly. For further heat-treatment intended to

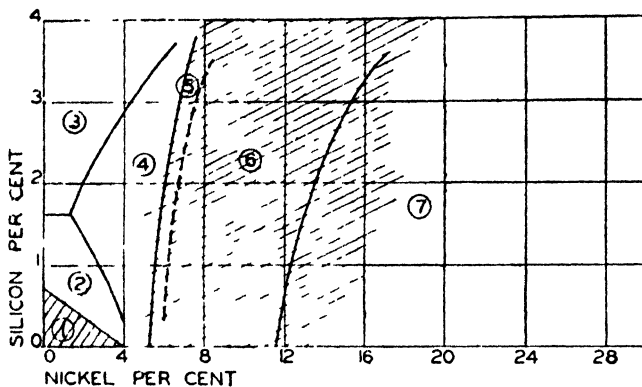


FIG. 47. SHOWING EFFECT OF NICKEL AND SILICON ON THE CONSTITUTION OF 3.5 PER CENT CAST IRON.

- 1 Pearlite + Austenite + Cementite + Eutectic
- 2 Pearlite + Pro-eutectoid Cementite + Graphite
- 3 Pearlite + Graphite
- 4 Sorbite + Graphite
- 5 Martensite + Graphite
- 6 Martensite + Austenite + Graphite
- 7 Austenite + Graphite

produce a sorbitic ground mass the castings are reheated to a temperature about 20°C . above the A_c3 critical point, i.e. 820°C to 850°C , and quenched in oil. They are then tempered by reheating to 640°C . for about 30 min. and quenched in oil, finally being subjected to a low temperature annealing at 450°C in order to remove hardening stresses.

The microstructures of ordinary and heat-treated cast iron by the Piwowsky process are shown in Figs. 45 and 46. The eutectic graphite in some cases can only be resolved at a magnification of 500 diameters, a striking contrast to the coarse flakes usually seen in cast iron. The ground mass after heat-treatment can only occasionally be resolved into a very fine-grained granular pearlite.

Martensitic Cast Irons

These are hard varieties of iron containing martensite intended for use under conditions of severe abrasion for resistance to wear; they are very hard and difficult to machine as a rule.

The addition of 6 to 7 per cent of nickel will give the desired change, first from a pearlite matrix into sorbite and then into martensite; the combined carbon is normal and the fracture is grey.

The effect of the nickel in conjunction with silicon up to 4 per cent upon the constitution of 3.5 per cent carbon iron is illustrated in Fig. 47, the shaded areas of which indicate the ranges of unmachinability.

There are *two classes of martensitic iron*, namely: (1) That in which the eutectic filling surrounding the primary grains is allowed to solidify to the white or cementitic condition; (2) that in which it

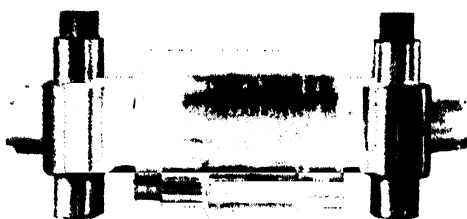


FIG. 48. GROUP OF NI-HARD ROLLS
(J. Fowler Ltd.)

solidifies grey or graphitic. The latter condition can be obtained in the cast condition or produced by suitable heat-treatment

A typical martensitic cast iron has the following percentage composition: Total C, 2.95; Si, 0.80; Mn, 0.40; Ni, 4.86; Cr, 1.55. This iron has a mean coefficient of expansion of 10.38×10^{-6} per degree C. from 0° to 250° C.

Automobile cylinders of this iron give several times the useful life, before re-boring or grinding is necessary, of ordinary plain iron ones. Parts of grinding machinery are also made of this iron.

It may be mentioned that cast iron with smaller additions of nickel (generally of the order of 3 to 5 per cent) can, as in the case of steels, be heat-treated so as to develop this specially hard structure. This is of great advantage in the case of castings which can be subjected to such treatment, though clearly it is applicable only to simple castings such as cylinder liners. In such cases, however, a readily machinable casting can be made in the first place which, after machining, can be subjected to a single quenching operation in oil or air followed by grinding to final size. After this treatment the castings possess the usual properties shown by ferrous materials in the martensitic condition.

Martensitic irons can be machined by using tungsten carbide and similar cutting tools.

A typical example of a martensitic iron is that known as *Ni-Hard*, a nickel-chromium white iron of great hardness; it contains 4.5 per cent nickel and 1.5 per cent chromium.

Ni-Hard has from 6 to 8 times the abrasive resistance of ordinary white cast iron; it can be used as a hard facing or surfacing material

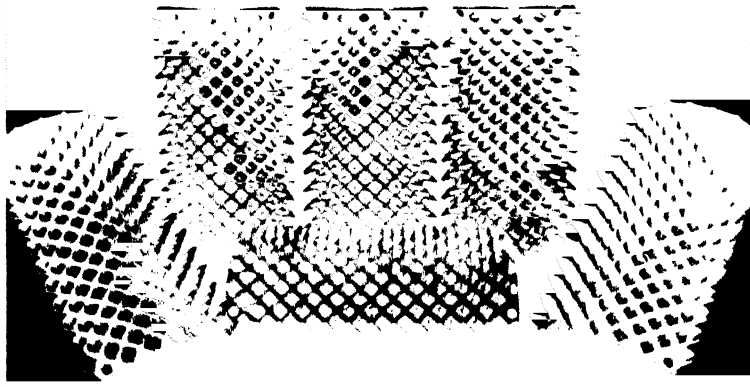


FIG. 49. NI-HARD CAST IRON SEGMENTS OF A COKE CRUSHER
(Bureau of Information on Nickel)

to other cast irons by welding processes. The tensile strengths of the 2.75 and 3.5 per cent carbon Ni-Hard irons are 31 to 36 and 25 to 27 tons per sq. in., respectively, for the chilled sections and 18 to 22 and 13 to 16 tons per sq. in. for the grey core. The Brinell hardnesses of the chilled face are 575 and 650 to 700 respectively.

Applications of Martensitic Irons

The *grey martensitic iron* is employed for castings of automobile cylinder liners, grinding machine rests and drums; scraper blades and ash-handling pump impellers and wear plates.

The grades of grey martensitic iron in which the martensitic structure is developed by heat-treatment are employed for air-cooled motor-cycle cylinders, liners for automobile cylinders; valve guides; cams for textile machinery; die inserts; jig bushings; jigs and fixtures, light blanking dies, forming and small press dies, etc.

The *white martensitic irons*, of which Ni-Hard is typical, are used for ash discharge doors, pump bodies and impellers; ball mill trunnions;

ball and rod mill liners, feeder lips and scoops; brick mould liners; cable car pulleys; centreless grinding machine blades; clay pipe dies; concrete pump liners and plungers; dredger pump bodies and impellers; dust-collecting valves; fan blades for pulverized coal; mill balls, pan bottoms and plates; mill guides; mixer arms; mine car wheels; plough points and shares; pug knives; pump rams; metal working rolls; sand and shot blast nozzles; tumbling barrel liners; stamp mill heads and shoes and scraper blades.



FIG. 50. HOT MOULD CAST IRON. SHOWING LAMELLAR PEARLITE AND PHOSPHIDE STRUCTURE. $\times 500$

Hot Mould Cast Irons

These irons consist of medium-carbon low-silicon mixtures produced in preheated moulds for the purpose of delaying the rate of cooling. Typical examples of such irons are those of the previously mentioned Lanz and the Diefenthaler. The silicon proportion employed, the mould temperature and metal section are adjusted so as to give a uniform all-pearlitic structure in various shapes and sizes of sections. Usually, the amount of silicon employed varies inversely as the thickness of the casting section, but normally it is lower than for ordinary irons. The mould temperature does not generally exceed 400°C . to 500°C . The tensile strengths of such irons are from 14 to 18 tons per sq. in.

The following is a typical percentage composition for an iron used in the Diefenthaler process: Total C, 3.00; combined C, 0.74; Si, 0.46; Mn, 1.15; S, 0.11; P, 0.14.

A bar 1 in. square by 6 in. long, cut from the casting mentioned, gave a tensile test of 13.8 tons per sq. in. on a gauge length machined to 0.564 in., the Brinell hardness on the end of the tensile specimen being 201.

For a separately cast bar of metal, 1.25 in. diameter and 18 in. long, of similar analysis, when machined to 0.798 in. diameter, the tensile strength was 17.3 tons per sq. in. The Brinell hardness was 223. The bar gave a modulus of rupture in a transverse test of 33 tons per sq. in., the deflection at fracture being 0.39 in.

A special feature of hot mould irons is their *low growth*; this is considerably less than for sand castings. Thus, in the case of some commercial hot mould irons tested by C. E. Pearson, two castings were heated for one hour at 900° C., the procedure being repeated forty times, when the increase in volume measured was 5.5 per cent. Other sand castings in commercial irons showed increases of 16 to 37 per cent. The iron in question contained 3.33 per cent C and 0.48 per cent Si.

These irons are used for steam and Diesel cylinders, heads, liners and pistons, turbine castings, e.g. bedplates, I.P. and L.P. casings and diaphragms, etc.

Other Special Cast Irons

It is not possible, owing to space considerations, to deal with several other special grades of cast iron employed for particular purposes, but the following is a convenient summary of the more important of these irons —

1. High-silicon cast iron with 4–10 per cent silicon for heat resistance, known as “Silal”

2. High-silicon cast iron with silicon present up to 13–18 per cent, brittle but highly resistant to acids.

3. High-chromium cast iron, containing 20–35 per cent chromium, used for heat- and corrosion-resisting castings.

4. High-aluminium cast iron, for heat-resisting castings, containing about 8 per cent aluminium and also some chromium.

5. Irons cemented or otherwise surface-treated to produce special skin properties for resisting heat or wear.

6. Nitrogen-hardened cast iron: irons of special composition containing 1.5–2.0 per cent each of aluminium and chromium are submitted to a special treatment to produce a very high surface hardness (diamond) of the order of 1000 Vickers diamond hardness. These irons are dealt with in Chapter VII.

Growth of Cast Iron

When graphitic cast iron is subjected to repeated heating to moderately high temperatures and coolings it is found to increase in volume, this effect being a permanent one. From the point of view of internal combustion engine cylinders, exhaust manifolds, furnace bars and castings, this property is a disadvantageous one, but fortunately it has now been overcome to a considerable degree. It is believed*

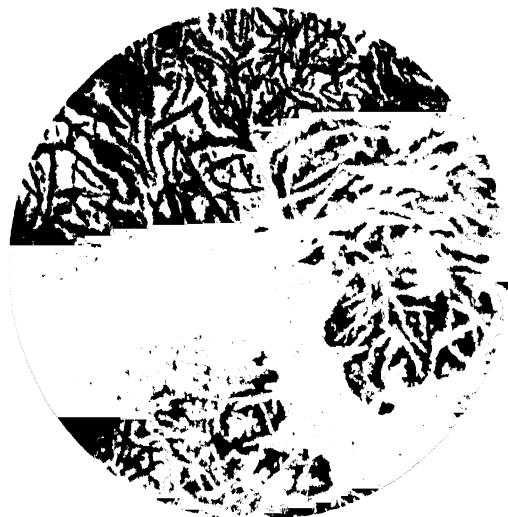


FIG. 51. SECTION OF "GROWN" CAST IRON ANNEALING POL., SHOWING OXIDE FORMATION ALONG GRAPHITE FLAKES. $\times 50$.

that the permanent increase in volume is due to the oxidation of iron silicide in solution in the iron, with the production of ferric oxide and silica, which occupy a greater volume than the original iron silicide; the oxidizing gases penetrate through slits existing between the graphite flakes and the metallic iron in grey cast iron.

Apart from the oxidation theory, most investigators agree that the gases dissolved in the iron may, under certain conditions, play an important part in promoting growth, especially where the silica content is low. It has been found that a fluctuating temperature results in a greater degree of growth than a steady temperature. The greatest growth occurs when the range of temperature includes the α to γ change of the iron.

* A résumé is given in the *Bulletin of the Cast Iron Research Association* for April, 1928.

The growth of grey cast iron has been known to cause an ultimate increase in volume by as much as 30 per cent. in extreme cases, as when castings have been repeatedly heated to temperatures of 850° C. to 950° C. and cooled.

The growth of cast iron at temperatures below the critical range is much less marked, but it has been noted in parts exposed to superheated steam at 300° C. Alternately heating and cooling is not so essential for growth at these lower temperatures. The results of Donaldson and others indicate that at first the decomposition of the carbide is responsible for a good deal of the growth, but that at a later stage the effect of oxidation again becomes pronounced. For this reason it is important to have a stable carbide present in cast-iron parts of engineering materials which are subjected to such temperatures.

The rate at which growth takes place may be minimized by exercising control over the composition of the iron. Broadly speaking, compositions to be aimed at are those which tend to produce chill. Low carbon and silicon contents are advisable. High sulphur is not desirable, although it appears to retard growth except when neutralized by the presence of manganese. Generally speaking, phosphorus is very undesirable when the cast iron is to be used at exceedingly high temperatures—800° C. to 900° C., but at low working temperatures its presence is said to be advantageous.

Many investigators have added various special elements, such as chromium and tungsten, to cast iron, with a view to stabilizing the carbide. It is believed that chromium exerts a decidedly beneficial influence in retarding growth, but the limits within which it may be added are very narrow.

Some of the more recent alloy cast irons mentioned previously, such as Nicrosilal and hot mould cast irons, experience very little growth, due to their special constituents. The austenitic irons possess exceptionally good growth-resistant qualities. This is illustrated by the results* shown in Fig. 52 for an ordinary iron (A) and austenitic iron (B), subject to the same heating and cooling cycles of 1500° F. for 8 hours. After 40 cycles it will be seen that the growth of the austenitic iron is only about one-fourteenth that of the plain iron.

In order to take account of "growth" in automobile and Diesel engine castings, such as cylinders, pistons, and liners, it is usual to subject the castings to a seasoning process which often consists in heating them to 750° C. to 850° C. and allowing them to cool slowly in the furnace after the heat has been shut off. Afterwards the castings are placed aside for a period of time of one to three months

* Vanick and Merica.

in order to allow any permanent growth to occur. The castings are then machined and placed in service.

The process in question not only obviates the effects of growth but also relieves the material of the effects of casting stresses and chills. In some instances, e.g. for cast-iron pistons, these are first given a rough cut to remove the surface skin and then subjected to the seasoning process mentioned.

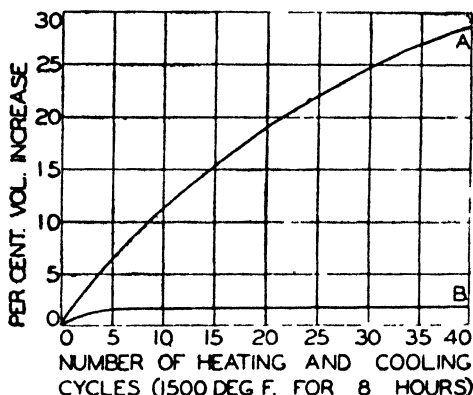


FIG. 52. ILLUSTRATING GROWTH OF CAST IRONS A, ORDINARY IRON B, AUSTENITIC IRON

Centrifugal Castings

A method employed in the production of castings of hollow cylindrical form in order to ensure perfect homogeneity and freedom from gas inclusions and other defects utilizes centrifugal action to attain these qualities; it is used primarily for making piston rings and cylinder liners for internal combustion engines.

A comparison of the ordinary vertical sand casting and the centrifugal casting methods is illustrated. In Fig. 53 (A) the defects of the vertical method of casting liners in a mould are shown. The molten metal in the mould begins to solidify almost simultaneously on both the internal and external walls, and solid walls of metal are formed with the liquid metal remaining in between. As the solid metal increases the gases are concentrated in the still remaining liquid portions of the metal in the centre of the radial thickness of the casting, and if the concentration reached is high enough, the gases evolved must either find their way out through the whole length of the casting or be entrapped in the radial thickness of the wall.

There is also a tendency for the insoluble constituents, such as

manganese sulphide, to segregate into the last portions of the liquid metal to solidify. This explains the segregations found in cylindrical castings in or about the centre of the radial thickness.

In the centrifugal method (Fig. 53 (B)) the inner surface of the metal is the last to solidify.

In the centrifugal process the mould is filled with metal in a direction at right angles to that in which the filling takes place in the vertical sand mould, and solidification of the metal commences from the outside

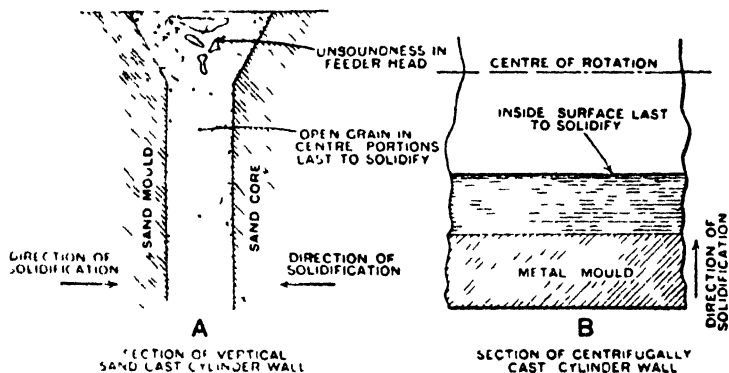


FIG. 53 ILLUSTRATING CENTRIFUGAL METHOD OF CASTING IRON

surface only and proceeds across the radial thickness of the casting progressively until the whole is finally solid, the inner surface layers being the last to solidify. At the instant solidification commences, the metal lying against the mould wall is liquid and has acquired the rotational velocity of the mould. Under these conditions a centrifugal pressure gradient is established across the radial thickness of molten metal, the pressure being at a maximum in the outside diameter layers of molten metal and zero on the extreme inside diameter layers. This maximum pressure is often of the order of 500 lb. per sq. in. The dissolved gases liberated by the solidifying layers, which first commence to solidify on the outside surface, must make their way through the radial thickness of still liquid metal; this is a much shorter path than the vertical length of the casting in the vertical sand casting case. It is therefore practically impossible for blow-holes or internal unsoundness to exist in castings made by this method.

Spun-sorbite cylindrical castings, such as are produced on the Hurst machine (Fig. 54), are made by the centrifugal process from low-silicon, low carbon irons having the maximum carbon content for machinability. The method uses a refractory sand-lined mould placed in a

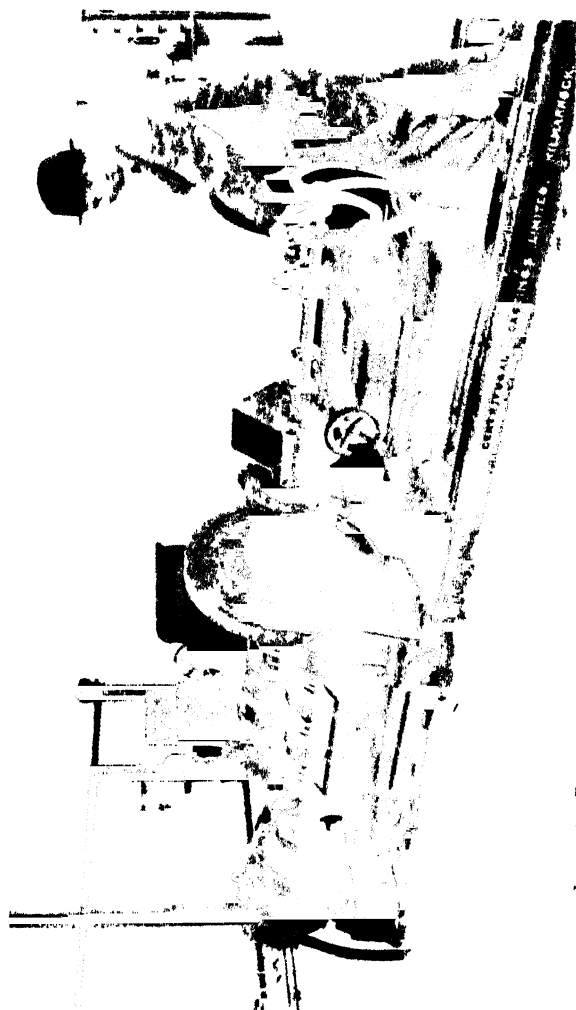


FIG. 4 THE OVERHUNG HURST BALL TYPE (CENTRIFUGAL CASTING, MACHINING)

special container which can be rotated at the desired speed. In this way cylinder liners for Diesel and other types of engine can be produced of sound structure and homogeneous. When the metal is



FIG. 55. NORMALLY COOLED CENTRIFUGAL CASTING OF LOW SILICON CONTENT SHOWING PEARLITIC STRUCTURE. 150



FIG. 56. SLOW SORBITIC CASTING SHOWING SORBITIC MATRIX. 150

allowed to cool down slowly the combined carbon is in the pearlitic condition. The cast iron thus obtained can be hardened by quenching from the appropriate temperature in water owing to the martensitic structure of the metal. If the rate of cooling is hastened somewhat

above the normal an intermediate sorbitic structure between pearlite and martensite is obtained still freely machinable. In this process the casting during cooling down is subjected to the action of a wet

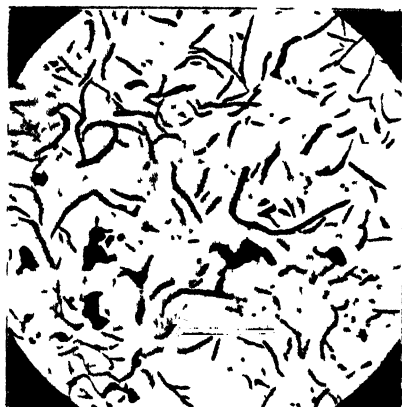


FIG. 57. SHOWING RELATIVELY LARGE FLAKES OF GRAPHITE IN ORDINARY CAST IRON. 33

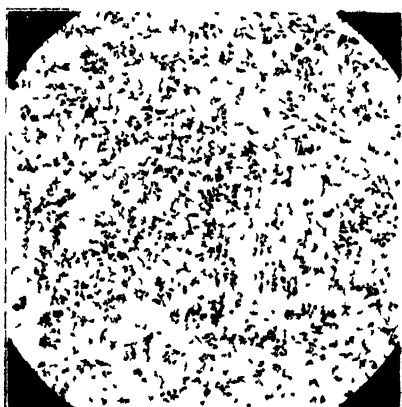


FIG. 58. FINELY DIVIDED GRAPHITE IN CENTRIFUGAL CASTINGS. 34

air blast, suitably regulated. The hastened cooling resulting from this treatment results in this sorbitic structure, this is distinctly advantageous, as it is highly resistant to wear.

A typical percentage composition of a spun sorbitic casting is as

follows: Total C, 3.00; combined C, 0.97; Si, 1.31; Mn, 0.42; S, 0.11; P, 0.34. The tensile strength of rings made to B.E.S.A. Specification No. 5004 varies from about 26 to 29 tons per sq. in. Austenitic irons are also used for centrifugal castings.

"Loded" Cast Iron

This is an "all pearlitic" cast iron, free from any ferrite, having a high silicon content, namely, from 2.5 up to 7.0 per cent. Many castings of "loded" iron have silicon contents of 4.5 to 5.5 per cent, stabilized by 1 to 4 per cent of chromium, adjusted to the silicon content and section of the castings to ensure the "all-pearlitic" structure.

The silicon and chromium may be replaced wholly or in part by manganese, nickel, copper, or molybdenum; in addition, small amounts of tungsten, vanadium, or titanium may be used.

"Loded" irons* possess great stability under high temperature conditions. They have the good bearing metal qualities associated with grey cast iron, favouring the holding of the oil film upon their working surfaces. They also have the property of quickly forming a working skin which strongly resists further wear. These irons are resistant to acidic attack, this resistance increasing with the silicon and chromium content. They possess a medium tensile strength, namely, about 17 tons per sq. in., at the present stage of development, for a 5 per cent silicon iron; the brittleness, however, increases with the silicon content.

The "loded" irons have a high natural hardness. Whilst ordinary grey irons become machinable at about 280 Brinell hardness, "loded" irons of 300 to 400 Brinell will machine satisfactorily.

These irons, owing to their pearlitic structure, have excellent wearing qualities which, coupled with their high heat resistance, render them especially suited to applications such as internal combustion engine cylinder piston rings and liners; the latter are usually of the spun or centrifugally cast type. In connection with the manufacture of these "loded" irons it may be mentioned that they can be produced with the usual foundry plant, although metallographic control is essential. In their manufacture it is desirable to aim at the inclusion of a small amount of cementite rather than the more exact pure pearlite and graphite structure alone, since in the latter case there may be some risk of ferrite inclusion and, in consequence, of much reduced wear and heat resistance.

* "Loded Cast Irons," H. J. Young, *Proc. Inst. Marine Engrs.*, December, 1934.

Cast Iron for Piston Rings

Hitherto plain cast iron has been used with satisfactory results, in regard to wear and elasticity, for piston rings of automobile engines. The B.E.S.A. Specification* for the material of piston rings of cast iron for *sand castings* is as follows: Total C, 3.50 (max.); combined C, 0.55-0.80; Si, 1.80 (max.); S, 0.12 (max.); P, 1.00 (max.); Mn, 0.40-1.20 (percentages).

For chill castings the percentage composition was: Total C, 3.5 (max.); combined C, 0.45-0.80; Si, 1.80-2.50; S, 0.12 (max.); P, 1.00 (max.); Mn, 0.40-1.20.

The combined carbon, upon which the pearlitic structure depends, is governed by the rate of cooling as well as the composition; the former factor, in turn, depends upon the thickness of section and type of mould, i.e. whether of metal or sand. The resulting mechanical properties, however, for the specified composition are the governing consideration, and in this connection it is usual to specify a tensile and also an elasticity test.

For the tensile test a test ring is cut from the pot to an approximately square section, or to that of the finished piston ring. It is then split and pulled apart in a testing machine by a load applied at opposite ends of the diameter, which is at right angles to that through the gap. It must withstand a stress of at least 16 tons per sq. in. before fracture as calculated by the formula

$$S = \frac{PD}{1200bt^2}$$

where S = stress in tons per sq. in.,

D = external diameter of ring in inches,

P = load in pounds,

b = width of ring in inches,

t = radial thickness of ring in inches.

The dimensional specifications of piston rings involve the maximum and minimum cylinder wall pressures exerted by the rings, as calculated from a formula having an elasticity constant determined under specified conditions. The elasticity thus obtained is referred to as the En value, and must not be less than 15.5 million lb. per sq. in.

In the case of centrifugally cast iron the value of En is generally exceeded by 1 to 2 million lb. per sq. in.

* No. 5004 (1927)

The formula employed is as follows—

$$En = \frac{5.37 \left(\frac{d}{t} - 1 \right)^3 \times Q}{bL}$$

where En = elasticity in lb. per sq. in.; Q = load (lb.) to close ring as indicated by gauge; d = mean external diameter of closed ring; b = breadth, and t = radial thickness of ring in inches. L = difference, in inches, in the length of the free gap caused by the load Q .

The method used is to take a circular ring blank from which has been machined a piece so as to leave a gap of 2.75 to 3.0 times the radial thickness. The ring is loaded by diametrical load.

More recently, piston rings have been made not only in cast irons such as rotary furnace synthetic cast iron and heat-treated grey cast iron, but also in alloy cast irons, including those containing copper, molybdenum, chromium, and nickel. Typical examples of these are Ni-Resist, Meehanite, nickel low silicon cast iron, and Brilybdenum.*

Cast Iron for Dies

Cast iron is employed in instances where the duties of dies are relatively light, or the life required is not great. For heavier duties and longer life alloy steel dies are generally employed.

The irons used for dies are chiefly the alloy ones, including those with nickel and chromium content. Ni-Tensyl is a typical example of an alloy iron used for dies.

The recommended alloy cast irons for various kinds of dies are conveniently classified in Table 13.†

For smaller dies such as those used for small channel sections, brake drums, etc., the irons given in V and VI are employed; the production results show that the heat-treated irons are ten times better than ordinary cast iron, and sometimes equal those of steel dies, although much cheaper to employ than the latter.

Thus, dies of this type have drawn 16,000 to 18,000 fender and body blanks as compared with 3000 blanks drawn on plain cast-iron dies. Heat-treated dies of the alloy irons produced 126,000 stampings with 3 hours dressing time, whereas under similar conditions plain iron ones produced only 12,000 stampings with 26 hours dressing time. Chassis frames and channels have been made with alloy iron dies (heat-treated), whilst radiator shells have also been produced with every satisfaction.

* British Piston Ring Co. Ltd., Coventry.

† *Alloy Cast Iron Dies*, Bureau of Information on Nickel Publication.

TABLE 13
ALLOY CAST IRONS FOR DIES

Type	I Alloy Cast Iron	II Ni-Tensyl	III Heat-treated Ni-Tensyl	IV Hard Alloy	V Heat-treatable	VI Air-hardening
Application	Large Press Dies	Large Press Dies Drop Forging, etc.	Light Blanking Dies Small Press Dies	Press Dies Drop Forging Hot Processing	Light Blanking Dies Small Press Dies Draw Dies Drop Forging	Light Blanking Dies Small Press Dies Draw Dies
Total Carbon	0.6-3.0	2.7-2.9	2.7-2.9	2.9-3.2	2.9-3.2	3.0-3.4
Silicon	0.8-1.5	1.25-1.75	1.25-1.75	1.0-1.5	1.0-1.5	1.0-1.5
Nickel	1.25-1.75	1.25-1.75	2.5-3.5	2.5-3.5	2.5-4.0	5.0-6.0
Chromium	0.4-0.8	—	—	0.6-1.0	0.6-1.0	1.0-1.5
Manganese	—	—	—	—	—	—
Sulphur	—	—	—	—	—	—
Phosphorus	—	—	—	—	—	—
The recommended contents for these elements are the same throughout the series, namely, Manganese 0.5-1.0, Sulphur less than 0.12, Phosphorus less than 0.3						
Treatment	Use as cast	Use as cast	Oil Quench 850° C. Temperature 350° C.	Use as cast	Oil Quench 850° C. Temperature 350° C.	Soften, Slow Cool from 680° C. Harden, Air Cool from 850° C. Machinable as cast
Machinability	Good	Excellent	Machinable as cast	Machinable	Machinable as cast	400 24
Breil Hardness	220	230	400	270	350	400
Tensile Strength, tons per sq. in.	18	25	30	22	25	24

Other instances of the successful use of alloy iron dies include those for blanking and pressing sheet metals, steel beer kegs, automobile bumpers, wings, doors and panels, steel brake drums, domestic utensils, and drop forgings. One important advantage of cast irons for dies and moulds is that the latter can be cast to approximately the final shape, thus saving a good deal of the expense attendant upon the die-sinking operations employed for steel dies and moulds.

Heat-resisting Alloy Irons

Although references have been made in preceding pages to certain alloy irons possessing good heat-resistance qualities, it will be convenient, here, to summarize these metals. Their main essentials include the retention of strength and hardness at higher temperatures—in some cases up to a red heat—combined with corrosion resistance, not possessed to anything approaching the extent by plain irons.

Austenitic irons offer a marked resistance to growth and oxidation; typical examples are Silal, Nimol, and Nicrosilal. The "loded" irons are also notable for their heat-resisting properties. Cronite,* a nickel-chromium cast iron, is another example of a suitable iron for high temperature application.

These irons are employed for the lehrs in glass bottle making machines, bottle moulds, mushroom valves in producer gas plant, producer gas burner parts, exhaust valves and seatings for Diesel engines, burner nozzles of pulverized fuel and oil installations, pyrometer sheaths, retorts for activated carbon manufacture, annealing pots, muffle furnace parts, grates for boilers and gas producer plant, test retorts, etc.

In regard to the use of alloy irons for pulverized fuel nozzles, it may be mentioned that Cronite nozzles have been shown to last thirty times as long as cast iron nozzles at 1000° C. (1832° F.) and castings of such alloy irons will give continuous service at 1050° C. to 1100° C.

An aluminium-chromium cast iron, known as "Cralfer," has also given excellent service under high temperature conditions. Irons containing silicon and aluminium are liable to be brittle when cold, but much stronger at operating temperatures than pearlitic irons.

Corrosion-resisting Alloy Irons

These irons include the high-silicon ones, previously mentioned; also the high-chromium ones. Austenitic irons such as Ni-Resist and Nicrosilal are also used in cases where plain irons are not sufficiently

* Cronite Foundry Co. Ltd., Tottenham.

resistant to corrosion, being from 3 to 600 times as resistant as pearlitic iron, according to the attacking medium.

High-silicon irons (up to 15 per cent Si) have been used to a marked extent in chemical plant and are probably the most acid-resistant ferrous metals at present in use. The castings are usually given a low-temperature heat-treatment before use.

High-chromium irons (10 per cent Cr) combine a high resistance to corrosion with a similar resistance to heat and erosion: they are especially suitable for parts exposed to the action of sulphurous gases. The "loded" irons are also resistant to corrosive influence; this resistance increases with the silicon and chromium content.

Nimol is another example of a corrosion-resisting alloy, which also has good heat-resistance properties up to 850° C. It is about 100 times as resistant to acids as plain iron and strongly resistant to atmospheric corrosion. It is significant that the hard casting skin of all commercial irons is more resistant to corrosion than the inner metal and that hard dense castings also offer a greater resistance.

Hypercrod is a high-temperature resistance alloy cast iron having from 12 to 15 per cent nickel, 6 to 7 per cent copper, 1.5 to 5.0 per cent chromium.

Irons for Pressure Castings

For these castings a very close-grained structure combined with high tensile strength are of primary importance. Hydraulic and Diesel cylinder castings come under this heading. They are usually alloy irons containing nickel, molybdenum, and vanadium. A typical alloy contains 0.41 per cent chromium; 0.23 per cent molybdenum and 1.03 per cent of nickel. It has a tensile strength of 27 tons per sq. in. at the centre portion of a 2-in. section.

Some typical compositions and strength values for high-pressure casting irons are given in Table 14.*

Cast-iron Crankshafts and Camshafts

High-duty cast iron has been employed successfully for the crankshafts and camshafts of oil and petrol engines, including motor car types. The irons used for this purpose include copper-chromium ones, inoculated iron, chrome-molybdenum and nickel-chromium irons.

In this connection the cast-iron crankshaft, provided that it possesses the necessary strength and hardness qualities, offers some definite advantages over alloy steel ones, except in the high-performance petrol engine field, as instanced by the aircraft engine. It is cheaper

* "Alloy Irons in Engineering," R. Lowe, *Journ. Inst. Engrs.*

TABLE 14
ALLOY CAST IRONS FOR HIGH-PRESSURE CASTINGS

Application	C %	Mn %	Cr %	Mo %	Ni %	Tensile Strength Tons per sq. in.	Transverse Test Lb. per sq. in.	Brinell Hardness
Valve Bodies (Cr-Mo)	3.21	2.16	0.31	0.41	—	20.5	2,900	248
Valve Bodies (Ni-Cr-Mo)	3.27	1.77	0.36	0.77	0.78	22.3	3,000	269
High-pressure Pumps (1)	2.90	0.95	0.27	0.27	1.80	17.9	9,000*	248—2 in. sec.
High-pressure Pumps (2)	3.16	1.36	0.41	0.73	1.03	27.0	11,340*	277—2 in. sec.
High-pressure Pumps (3)	3.00	1.70	0.83	0.71	1.25	25.7	3,300	269
High-pressure Pumps (4)	2.85	2.60	—	0.57	—	23.9	3,170	255

* Bars broken on 24-in. centres.

to produce in the blank form than the forged crankshaft and requires fewer machining operations; further, a much smaller weight of metal needs to be removed in machining. Other advantages claimed include an actual reduction of weight, reduced frictional coefficient, and improved resistance to fatigue failures.

To illustrate the advantages claimed, mention will be made of the cast crankshafts used in Ford Vee Eight engines since about 1934. The material employed is a copper-chromium iron of the following percentage composition * C, 1.25-1.40, Si, 1.90-2.10, Mn, 0.50-0.60, S, 0.06 (max.), P, 0.10 (max.), Cu, 2.50-2.75, Cr, 0.35-0.40.

The cast crankshaft before machining weighed 65 lb. after machining 56 lb. The forged crankshaft weighed 90 lb. before and 66 lb. after machining. Thus, the cast crankshaft was not only 10 lb. lighter, but only required the removal of 9 lb. of metal as against 24 lb. for the forged shaft.

In fabricating the cast crankshaft fifty-four operations were required compared with sixty-two for the forged one.

The Brinell hardness averaged about 300. Fatigue tests made on finished crankshafts indicated twice the resistance to failure of forged shafts. All of the crankshafts were given a torque test of 40,000 lb. per sq. in. in both directions, this was about ten times the calculated maximum stress occurring in service. Tests of the frictional coefficient indicated that this was lower than for the steel crankshaft.

Later examples of copper-chromium crankshafts made from metal melted in the electric furnace had the following percentage composition: Total C, 1.35-1.60, Si, 0.85-1.10, Mn, 0.60-0.80, Cu, 1.50-2.00, Cr, 0.40-0.50.

This alloy iron was heat-treated by holding at 900° C. for 20 min. and air quenching to 1200° F. It was then reheated to 820° C. and held at this temperature for one hour. Afterwards it was cooled for one hour in the furnace, when its temperature fell to 540° C., and then allowed to cool slowly to air temperature.

The iron then had a tensile strength of 42.5-49.0 tons per sq. in. with 2.5-3.0 per cent elongation. The Brinell hardness was 250 to 320.

Another satisfactory alloy iron for crankshafts is a *nickel-molybdenum* one of the following percentage composition: Total C, 2.40-2.80; Si, 2.25-2.75; S, 0.10 (max.), P, 0.15 (max.); Mn, 0.80-1.20, Ni, 1.00-1.20; Mo, 1.00-1.20. The tensile strength is 27-36 tons per sq. in. and the Brinell hardness (as cast) from 255 to 320.

Tests made on a chromium-molybdenum iron cast crankshaft

* *Automotive Industries*, 17th March, 1934.

† F. J. Walls, *Journ. Soc. Automotive Engrs.*, U.S.A., 1938.

fitted to a four-cylinder commercial vehicle engine* of 74 h.p. (at 2500 r.p.m.) over a period of two and a half years, during which about 40,000 miles were covered, showed that at the end of this period the wear on the main bearings was between 0.001 and 0.002 in., whilst that on the crankpin journals was negligible. The big-end bearings were of "R.R.56" alloy and were in perfect condition, having an average running clearance of 0.003 in.

The percentage composition of the iron used was as follows: C, 3.00; Si, 1.80; Mn, 1.00; S, 0.05; P, 0.20; Cr, 0.21; Mo, 0.78. This metal gave a safe limiting fatigue stress (Wöhler) of 7 tons per sq. in. and a Young's modulus of 18×10^6 lb. per sq. in.

Another interesting example of a crankshaft alloy iron, with a nickel and molybdenum content, having a tensile strength of 63.2 tons per sq. in. is that mentioned on page 70.

Crankshafts of this material have been used in several thousands of American cars, trucks, tractors, marine and stationary engines.

The alloy in question, known as "Proferall X" (processed ferrous alloyed) is made either from metal duplexed in the electric furnace from the cupola or cold-melted in an electric furnace. It requires no further heat-treatment.

The Ford crankshafts are cast in units of four, vertically. After removal from the sand moulds, they are inspected and then the gates are taken off. The four-shaft unit as cast weighs from 420 to 425 lb. Owing to the difficulty of machining the iron special hammered high-speed tools are used. The working speeds of the machine tools have been reduced, but the rates of tool feed are the same as for forged shafts. Lathe speeds are reduced to about one-half and spindle speeds on drills, reamers, and tappers by 35 to 40 per cent.

Ni-Tensyl iron has also been employed successfully for crankshafts of Diesel engines of tractors, etc., over a period of several years.

A fairly complete investigation of alloy irons applicable to crankshafts has been made by Gough and Pollard.† The irons included copper-chromium, inoculated iron, chrome-molybdenum, and nickel-chromium; an alloy steel containing nickel, chromium, molybdenum, and copper, which was employed for cast crankshafts, was also included. It is not possible in the present limited space to give particulars of the compositions, heat-treatments, and mechanical tests made; reference should be made to the original paper for these. The results of the mechanical tests, however, are given in summarized form in Table 15.

* *Ibid.*, page 70.

† "The Properties of Some Materials for Crankshafts," *Proc. Inst. Autom. Engrs.*, March, 1937.

TABLE 15

MECHANICAL PROPERTIES OF CRANKSHAFT MATERIALS

Material	Alloy Steel	(chrome chromium Iron)	Inoculated Iron	(chrome molybdenum Iron)	Nickel-chrome Iron
Tensile limit of proportionality, tons per sq. in.	31.0	15.5	2.5	2.5	2.2
Yield point in tension, tons per sq. in.	43.8	None	None	None	None
Ultimate tensile strength, tons per sq. in.	52.3	32.3	23.3	20.8	18.8
Elongation ($l = 4 \sqrt{A}$) at fracture, per cent	10	0.2	0.4	0.8	0.8
Reduction of area at fracture, per cent	16	Negligible	0.4	Negligible	Negligible
Young's modulus E , lb. per sq. in. $\times 10^6$	29.3	26.8	21.7	26.1	18.7
<hr/>					
Brunell hardness number	260	260	245	280	265
<hr/>					
Torsional limit of proportionality, tons per sq. in.	17.3	1.0	4.3	2.7	2.7
Yield point in torsion, tons per sq. in.	33.0	None	None	None	None
Torsional modulus of rupture, tons per sq. in.	46.0	38.6	31.9	32.7	21.1
Total twist at fracture ($L = 8 \frac{1}{2}$) degrees	846	16	82	53	16
Modulus of rigidity G , lb. per sq. in. $\times 10^6$	11.5	11.4	8.6	8.6	7.1
<hr/>					
Isoductile bar value, ft. lb.	24.8	1.2	1.5	0.8	0.4
<hr/>					
Wöhler fatigue limit, tons per sq. in.	± 22.3	± 1	± 1.3	± 9.4	± 8.9
Alternating torsional fatigue limit, tons per sq. in.	1400 - 1200	1470	97	84	± 71

Chill Castings

Castings in plain cast irons having a very hard skin which gives excellent wear resistance are made by accelerating the cooling of the surface iron in the mould usually by the use of metal moulds. The

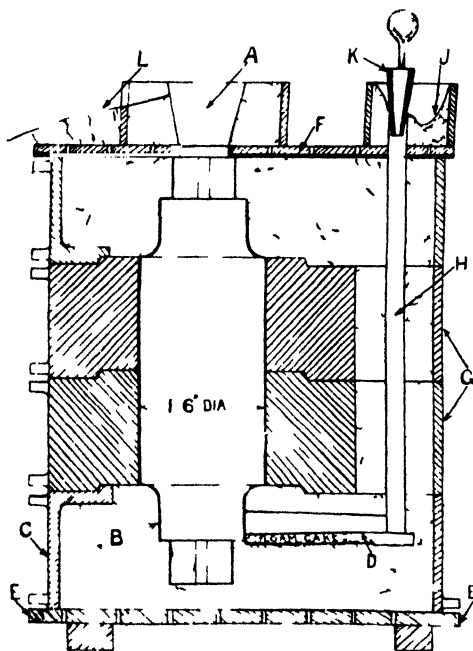


FIG. 58 METHOD OF CASTING A CHILLED ROLL IN IRON

pouring temperature and composition of the metal have important influences on the production of the chill.

Fig. 59 illustrates the method of casting a chilled roll*. The roll is cast vertically in a composite sand and cast-iron mould. In casting the roll the metal is poured into the basin *I* where it flows down *H* and along *D* to the mould *B*. As this fills the gate plug *K* is withdrawn by a long rod through its loop.

The function of the gate plug it may be observed is to prevent the scum from entering the mould. As the basin fills the scum rises to the top of the latter and the heavier (clean) metal on the withdrawal

* *Hardening Cast Iron by Chilling*. J. C. Edwards. *Metal Industry*, 36 (November 1923).

of the plug, is thus given priority of entrance. Channel *L* is a provision made to keep within bounds the overflowing metal from *A*, as the mould becomes filled, the surplus metal running off into previously prepared pig moulds.

In Fig. 59 the shaded portions, which include *C*, *E*, *F*, and *G*, represent the metal portions of the mould; the two central sections around the roll mould are of metal.

As is well known, these rolls require a very large amount of rod feeding. This occupies sometimes twelve or more hours, and calls for a continuous provision of hot metal.

It is found, in the case of most cast metals, that the rate at which the metal is cooled after casting has a considerable influence upon its mechanical properties.

In ordinary sand casting the sand is a poor heat conductor, and only slow cooling occurs, whereas if the mould is made of a metal suitably faced with a loam wash, much more rapid cooling occurs, the casting being extremely hard and having a silvery fracture. It is possible to arrange for certain areas of a casting to be chilled whilst others are in a softer condition: metal inserts are used in the sand or loam moulds for this purpose.

The wide range of applications of chilled-iron castings covers plough breast plates of only $\frac{1}{4}$ in. thickness to large metal rolls of 3 ft. to 4 ft. in diameter, weighing up to 30 tons.

The quality or hardness of the chill depends upon the extent to which carbon can be retained in its combined form, and the lower its graphitic proportion the better is the chilled metal.

Silicon also plays an important part in controlling the final constitution.

Longmuir recommends the following proportions of silicon (the other elements being in their correct proportions) for different depths of chill —

Depth of chill	$\frac{1}{4}$ in.	$\frac{1}{2}$ in.	$\frac{3}{4}$ in.	1 in.	$1\frac{1}{2}$ in.
% Silicon	1.00	0.70	0.52	0.40	0.40

The composition of the iron employed by different iron-founders varies, but most authorities agree that *fast melting* and *hot pouring* temperatures, and *low silicon* and *sulphur* contents are desirable.

A typical percentage composition for an iron suitable for chilled castings is as follows: Total C, 3.3-3.4; Si, 0.75-1.00; S, 0.08-0.10; P, 0.20-0.40; Mn, 0.70-0.80.

Effect of Nickel on Chills. By the addition of suitable proportions of nickel and also chromium to the iron a marked increase in hardness and strength can be obtained, so that the brittleness and lack of

strength usually associated with chilled plain iron castings can be avoided. The addition of nickel has the effect of increasing the hardness of the matrix so as to render it air-hardening. The graphitizing influence of the nickel, however, must be counteracted; this can be done by adding chromium, but reduction of the silicon or increase of the manganese also has a similar but less marked effect.

Chromium tends to stabilize the carbides and has the direct effect of increasing the depth of chill in a chilled casting; in addition the hardness of the carbide masses is increased.

Generally about 1 per cent of chromium is necessary to $2\frac{1}{2}$ –4 per cent of nickel in order to balance the chill.

The carbides in a white iron usually have a Brinell hardness of about 700, whilst that of a pearlitic matrix is from 200 to 300.

Chill Hardnesses. In the case of a typical nickel-chromium iron, such as Ni-Hard the matrix hardness is between 500 and 700 so that the hardness of the chilled face is increased to about 700 to 800; at the same time the alloys mentioned refine and toughen both the chilled portion and the grey interior. For normal purposes, where *hardness is of primary and strength of secondary importance*, a high carbon content of 3·6 per cent or over should be employed. Where, however, castings are subjected to shock and maximum strength and toughness are required, then a low-carbon iron (2·5 to 2·8 per cent C) should be employed.

For the best results the silicon content must be reduced (to about 0·7 to 0·8 per cent) and the manganese increased (to about 0·8 to 1·2 per cent)

TABLE 16
TEST RESULTS FOR PLAIN AND NI-HARD IRONS

	Unalloyed Iron		Ni-Hard	
	High Carbon	Low Carbon	High Carbon	Low Carbon
Total carbon	3·50	2·75	3·50	2·75
Silicon	0·75	0·75	0·75	0·75
Nickel	—	—	4·50	4·50
Chromium	—	—	1·50	1·50
Brinell hardness of chilled surface .	500	400	650–700	575
Shore hardness on chill face .	70	55	90	78
Tensile strength in chilled section, tons per sq. in.	16–18	21–24	25–27	31–36
Tensile strength in grey core, tons per sq. in.	7–11	10–17·5	13–16	18–22

Sulphur is a powerful chilling agent, but tends to make castings brittle, in this respect, however, manganese has a preferential combination for sulphur, so that increased chill depth is obtained by the removal of the sulphur



FIG. 60. WHITE IRON CASTING BEFORE MALLEABILIZING. 100



FIG. 61. ENGLISH "BLACK HEART" IRON. $\times 100$

The temper carbon is embedded in soft ferrite, pearlite entirely decomposed

When Ni-Hard is used for chilled castings its composition should be adjusted to suit the type of casting, the higher carbon content composition (3.6 per cent C) with 4.5 per cent nickel and 1.5 per cent chromium being used for castings of maximum strength and the lower content (3.0 per cent C) with 4.5 per cent nickel and 1.0 per cent chromium for castings of light section and maximum strength.

The addition of 0.25 per cent molybdenum to the former type of iron renders it particularly suitable for heavy chill castings of maximum strength. Table 16 shows the results of tests on plain and Ni-Hard irons.

Malleable Cast Iron

This is a type of iron produced from cast-iron castings by a special heat-treatment process or "annealing," the iron having the general strength properties and some of the ductility of a good wrought iron, or in certain instances of mild steel.

The iron used for the castings is a white one, but a fairly wide range of compositions can be employed. There are, however, two classes of malleable iron, known respectively as the *White-heart* and *Black-heart* types, the latter have been extensively used in the U.S.A. for engineering and industrial applications.

The following are typical (average) percentage compositions* of the two kinds of iron.

	C	Si	Mn	P	S
White heart	3.25	0.55	0.15	0.25	0.06
Black heart	2.10	0.85	0.30	0.06	0.10

There are two stages in the production of malleable iron, namely, (1) the making of the white iron castings, and (2) the heat-treatment process.

In the first stage all of the carbon exists in the form of carbides, viz., iron carbide or cementite, characteristic of hard white cast iron.

The second stage, in the case of white-heart malleable iron, consists in heating the castings to a temperature of 900 C. to 1000 C., in contact with oxide of iron or powdered red haematite for a period varying from several hours to a day or two in order to reduce the carbides and finally oxidize them so as to free the iron from carbon. Owing to the low manganese and high sulphur content of white heart iron, and the consequent stabilizing effect of these upon the carbide, it is not possible to produce an entirely ferrite matrix, so that the structure of the malleable iron, when fully annealed, consists of an outer layer of practically pure iron, inside of which are iron and pearlite gradually

* "Malleable Cast Iron as an Engineering Material," C. C. Hodgson, *Machinery*, 7th December, 1933.

increasing in carbon content until the inner portions, which usually consist of pearlite at about 0.9 per cent carbon, are reached, and finally at the centre the structure consists of pearlite and graphite.

Black-heart iron is given a different heat-treatment, the use of the oxidizing medium being dispensed with. The annealing of the hard white castings consists in heating them to 860 °C. to 890 °C., followed by a slow rate of cooling. Usually, for both grades of malleable iron, the castings are allowed to cool in the furnace after the heat has been shut off.

In the first part of the annealing process the cementite is broken down and precipitated as graphite and iron. In the final stage the resulting matrix of iron containing carbon has its carbon converted into graphite. The resulting structure, in contrast to that of white-heart iron, is a uniform one consisting of a completely ferritic matrix.

The *silicon* content is adjusted to suit the size or section of casting; it has the effect of promoting the formation of graphite during heat-treatment. The proportion of silicon depends upon that of the carbon in the original iron, and as the latter is increased the silicon should be reduced in order to prevent the formation of graphite in the original castings during solidification and cooling.

Sulphur has the effect of stabilizing the carbon in the combined form, i.e. the cementite, whilst *manganese* tends to combine with the sulphur to form manganese sulphide, a product which has no stabilizing action on the iron carbide.

It is therefore usual to adjust the manganese to suit the sulphur content. Thus for 0.04 per cent S, from 0.20 to 0.24 per cent Mn is allowed, and for 0.10 per cent S, 0.27 to 0.34 per cent Mn in the case of black-heart castings.

Mechanical Properties. The strength properties of white-heart malleable iron vary considerably with the composition and section or dimensions of the casting.

The British Standards Institution specifies a tensile strength, for a 0.564 in. diameter specimen, of 20 tons per sq. in. (min.), with not less than 5 per cent elongation on 2 in., and for the bend test on an 8 × 1 × $\frac{3}{8}$ in. specimen not less than 45°. In practice, tensile strengths for white-heart malleable irons range from about 24 to 30 tons per sq. in., with elongations of 5 to 10 per cent and bend test angles of 45° to 90°.

For black-heart malleable irons the B.S.I. specifies a tensile strength of 20 tons per sq. in. (min.), elongation of 7½ per cent, and bend test figure of 90°.

These results show that the latter variety of iron is more ductile; it has not, however, the same wearing qualities as the white-heart

iron, but on account of its ferritic or soft iron structure it is easier to machine after the skin has been removed.

The average tensile strength of black-heart castings employed in the U.S.A.* is given as 24 tons per sq. in., with a yield point of 15 tons per sq. in. and elongation on 2 in. of 18 per cent. The modulus of elasticity in tension was 25×10^6 lb. per sq. in. and modulus of elasticity in shear 12.5×10^6 lb. per sq. in. The shearing strength is 21.5 tons per sq. in. and modulus of rupture in torsion 58,000 lb. per sq. in. The Brinell hardness is 100 to 140, the average value being 115.

Malleable-iron castings are, in general, cheaper to produce in quantity than iron or steel forgings and for this reason are widely used for purposes where higher strengths and ductilities are required than cast-iron castings provide. They are employed in various engineering applications, notably in railway work, road transport, shipbuilding, agricultural machinery, and the building and ironmongery trades.

Mitis Castings

These are wrought-iron castings made by adding from 0.05 to 0.09 per cent of aluminium to Swedish wrought iron or English haematite iron which has been melted. The effect of the aluminium is to lower the melting-point of the iron by some 300°C . or 400°C !. The iron is usually melted in a petroleum-fired furnace in crucibles of fireclay or plumbago.

It is important to keep the phosphorus content of the castings below about 0.10 per cent, otherwise brittle and unsound castings result.

The best Mitis castings possess all the properties of good wrought iron, being free from stratification and homogeneous in structure.

The tensile strength is often 20 per cent higher than that of wrought iron, whilst the ductility is about the same.

Commercial Applications of High-duty Cast Irons

Although a certain amount of information on the applications of various kinds of cast iron in engineering and industry has already been given, the following summary of these applications, with the inclusion of certain additional matter, may be found more convenient to potential users of such materials.

The method adopted is that employed by the I.M.E. Research Committee on High-duty Cast Irons (December, 1938); it enables the information sought to be ascertained in a ready manner.

The following is a list of the high-duty cast irons available, together with their key letters; the latter are used in the tables that follow.

* A.S.T.M. and Am. Foundrymen's Assoc. Symposium, 1931.

HIGH-DUTY CAST IRONS

Cast Irons Developed Especially for their High Strength

Cast iron using steel or refined pig iron	A
High-steel mix cast iron	B
Hot mould iron	C
Air furnace synthetic cast iron	D
Rotary furnace synthetic cast iron	E
Electric furnace synthetic cast iron	F
Nickel low-silicon cast iron	G
Nickel-chromium cast iron	H
Copper cast iron	J
Nickel chromium-molybdenum cast iron	K
Ni-Tensyl	L
Meehanite	M
Heat-treated grey cast iron	N

Cast Irons Developed for Special Properties with or without High Strength

Nickel martensitic iron	a
High-chromium cast iron	b
High-silicon cast iron	c
Ni-Hard	d
Nomag	e
Ni-Resist	f
Nicrosilal	g
Nitrogen-hardened cast iron	h
High-aluminum cast iron	j
Silal	k
Cemented cast iron	l
Special expansion cast irons	m

TABLE 17

CAST IRONS FOR AUTOMOBILE ENGINEERING*

	For General Use under Normal Conditions	For Special Conditions
Cylinder block	A	G, H, J
" head	A	G, H, J
" (air-cooled)	A	G, a
" liner	A, D, E, F	J, G, N, a, f, h
Crankcase	A	G
Flywheel	A	G, J, E, F, L, M
Piston		G, J
" rings		G, N, E, f
" carrier		f
Timing gears		N, G, J
Valve guides	A	N, H, J, a
Tappet head	A	H, d
Exhaust manifold	A	H, f
Clutch cone		H, A
" plate	A	G, H, L, J
" housing		A, G, H
Gearbox casing	A	A, G
Brake drums		E, H, G, K, J

* Including high-speed Diesel engines.

TABLE 18
CAST IRONS FOR SLOW AND MEDIUM SPEED DIESEL
ENGINES

	For General Use under Normal Conditions	For Special Conditions
Bedplate		A
Main frame		A, E, L
Crankcase cover		A
Cylinder jackets		A, F
heads	A, G	C, J, H, L
liners	A, F, G	C, H, K, L, M, J
Pistons	A, F, G	C, H, J
Piston rings		A, G, H, M
crown	A	C, H, J
Exhaust valve head	A	H, L
Cams		H, N
Timing gear		G, L, N
Flywheel	A, D	L, M

TABLE 19
CAST IRONS FOR STEAM ENGINES AND PUMP

Component	For General Use under Normal Conditions	For Special High duty Conditions
Cylinder and covers	A	C, G, H
Valve chest	A	C, G, J, M
Cylinder liner	A	C, G, H, J
Pistons	A	G, J
Piston rings	A	G
Flywheel	A	J
Bedplate (for turbines, etc.)		A, L
Water circulating pump		H, J
Fire bars and stoker fuels	A	C, H, M, b
Ash troughs		J

TABLE 20
CAST IRONS FOR MACHINE TOOLS AND DIES, ETC.

Component	For General Use under Normal Conditions	For Special High- duty Conditions
Machine tool frames	A	E, H, L, M
.. .. beds	A	E, L, M
.. .. tables	A	F, G, H, L
.. .. saddles	A	E, H, L
.. .. gears	A	F, G, H, L, M
.. .. pulleys	A, D	G, H, L, M
.. .. cams	A	F, F, H, L, M, N
.. .. chuck bodies	A	E, G, H
Press and draw dies	A, D	F, G, H, L, M
Drop forging dies	A	E, G, H, L, M
Blanking dies		N
Hammer blocks		D, L
Die casting dies	A	L, F, H, L

TABLE 21
CAST IRONS FOR MISCELLANEOUS INDUSTRIAL APPLICATIONS

Component	For General Use under Normal Conditions	For Special High- duty Conditions
Air compressor cylinder	A	G, H
.. .. piston	A	E, G, H, L, M
Oil crushing frame	A	L
.. .. jaw		d
Ball mill liners		d
.. .. balls		d
Locomotive firebars	A	H, b, f, g
.. .. superheater headers	A	G, H, K, L
.. .. cylinders	A	G, H
.. .. cylinder liners	A	E, G, H
.. .. pistons	A	E, G
.. .. piston rings	A	G
Electric generator end covers		c
.. .. resistance grids		c
.. .. hot-plate tops		G, H, M, f, g
.. .. furnace hearths		f, g
.. .. busbar chambers		o

TABLE 22
ALLOY CAST IRONS FOR MACHINE TOOL CASTINGS*

Application	C, %	Si, %	Mn, %	Ni, %	Mo, %	T.N.†	B.H.N.‡	Section
Lathe beds (light)	3.10	1.50	0.75	1.00	0.35	44,000	255	12 in.
Lathe beds (heavy)	3.10	1.25	0.75	0.50	0.50	47,000	255	2 in.
Turrets	3.25	1.25	0.90	—	0.35	45,000	262	12 in.
Columns	3.15	1.25	0.90	1.00	0.50	55,000	269	12 in.
Grinding machines (base)	3.25	1.75	0.75	0.75	0.60	50,000	248	12 in.
Tables	2.90	1.35	0.90	0.50	0.35	50,000	255	—
Forging hammer cylinders	3.00	1.10	0.80	1.00	0.60	48,000	255	2 in.
Forging hammer frames	3.14	1.50	0.60	0.68	0.35	45,350	248	12 in.
Header castings	2.60	2.60	0.85	0.62	1.20	83,900	341	12 in.

* R. Lowe. *Ibid.*, page 99.

† Tensile strength, lb. per sq. in. ‡ B.H.N.—Brinell hardness number

TABLE 23

ALLOY CAST IRONS FOR AUTOMOBILE PARTS*

Application	T.C. °	Si °	Mn °	Cr °	Mo °	Ni °	T.S.†	T.T.‡	R.H.N.§
Low Cr-Mo cylinder blocks . . .	3.30	1.90	0.80	0.25	0.20	-	43,700	2,810	228
Med. Cr-Mo cylinder blocks . . .	3.25	2.25	0.65	0.30	0.35	-	44,600	2,860	235
High Cr-Mo cylinder blocks . . .	3.10	2.20	0.70	0.30	0.65	-	52,700	3,200	289
Low Cr-Mo truck blocks . . .	3.25	2.15	0.85	0.35	0.35	-	46,700	2,960	241
Med. Cr-Mo truck blocks and heads . . .	3.25	2.15	0.85	0.65	0.60	-	51,700	3,200	262
High Cr-Mo truck blocks and heads . . .	3.20	2.10	0.80	0.70	1.00	-	57,700	3,300	302
Brake drums . . .	3.25	2.00	0.75	-	0.35	-	42,000	2,730	228
Brake drums . . .	3.00	2.20	0.75	0.35	0.40	-	48,000	3,000	241
Clutch plates Cr-Mo . . .	3.10	2.20	0.75	0.35	0.35	-	47,800	2,900	235
Pistons Cr-Mo . . .	3.15	2.50	0.75	0.30	0.35	-	46,000	2,700	228
Automotive flywheels . . .	3.40	1.60	0.85	0.35	0.25	-	44,600	3,000	228
Camshafts . . .	3.20	2.20	0.65	0.85	0.50	0.40	40,100	-	293
									286
Tappets . . .	3.40	2.60	0.50	-	0.60	-	-	-	57 R.C.
Tappets . . .	3.40	2.55	0.55	-	0.60	1.75	-	-	321 Brinell (grey section) 58 R.C. (chill)

* R. Lowe. *Ibid.*, page 99.

† Tensile strength, lb. per sq. in.

‡ Transverse test, lb.

§ B.H.N.--Brinell hardness number

TABLE 24
ALLOY CAST IRONS FOR DIESEL ENGINE PARTS*

Application	C	Si	Mn	Cr	Al	Ni	V	Fe	TT	RH
Diesel cylinder heads No. 1	3.20	2.00	0.80	0.60	1.00	—	—	—	—	341†
Diesel cylinder heads No. 2	3.60	1.60	0.80	0.40	0.90	—	—	—	—	277‡
Diesel cylinder heads No. 3	3.10	1.80	0.85	—	0.70	1.25	0.10	61 000	3 300	302‡
Diesel manifolds	3.60	1.45	0.50	0.25	1.00	—	—	46 000	2 800	302‡
No. 1 Diesel cylinder liners	2.90	2.10	0.80	0.40	0.85	0.40	—	51 000	3 180	269
No. 2 Diesel cylinder liners	3.10	2.10	0.85	0.60	1.05	—	—	52 700	3 210	277
No. 1 Diesel pistons	3.20	2.00	0.70	0.55	0.90	1.25	0.12	53 000	3 200	293‡
No. 2 Diesel pistons	2.55	1.60	0.70	0.25	0.70	1.70	—	67 500	3 500	248†
Diesel gars	3.20	1.60	0.70	0.40	0.60	1.15	—	56 700	3 300	269
Diesel cranks-shafts†	2.60	2.50	0.95	—	1.10	1.15	—	78 360	15 500	302
Liners (heat treated)	3.10	2.10	0.60	—	0.30	0.35	—	50 000§	4,600	240

* R. Lowe *Ibid.*, page 99. † Test bar hardness. Castings must be annealed to proper hardness.

‡ From an unnotched 1½ in. bar machined from 2 in. sec. impact - 100 ft. lb. § Heat treated.

CHAPTER IV

CARBON STEELS

THE name *steel* is given to practically pure iron containing carbon up to a maximum of 1.5 per cent together with small percentages of manganese, silicon, sulphur and phosphorus. In general carbon steels have a finer and more uniform structure than commercial irons and are practically free from defects such as slag and gas inclusions.

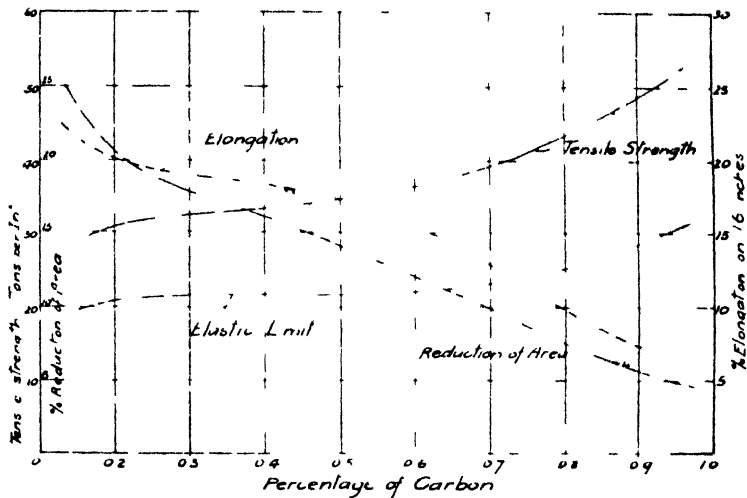


FIG. 62. EFFECT OF CARBON CONTENT UPON THE STRENGTH AND DUCTILITY OF STEEL.

The strength and hardness of steel increase with the percentage of carbon but the ductility and reduction of area under tensile test conditions decrease as the carbon content is raised. These properties are illustrated by the results of tests made by Bauschinger upon a number of steels of different carbon content, reproduced in Fig. 62. The Bessemer steels in question were not heat-treated, but in the ordinary rolled form. It will be observed from these test results that the elastic limit increases in a somewhat similar manner to the tensile strength, as the carbon increases.

The compressive strength and the elastic limit in compression both

increase with the carbon content. Thus, for 0.14 per cent carbon the elastic limit observed by Baischinger was 17.65 tons per sq. in.; for 0.55 per cent carbon, 22.22 tons per sq. in., and for 0.96 per cent carbon, 31.75 tons per sq. in.

In regard to the *shearing strength*, the corresponding values for 0.14, 0.55, and 0.96 per cent carbon were 21.7, 25.4, and 37.0 tons per sq. in. respectively. It should here be mentioned that the mechanical strength properties of carbon steels in the non-heat-treated condition depend also upon the proportions of the other elements, previously given, and upon the mechanical treatment to which the steel has been subjected. Thus, in the case of steel wire made by successive reductions of section by drawing the wire through very hard alloy steel or sintered carbide dies, the tensile strength and hardness are increased considerably. For example, a high-carbon steel rod having a tensile strength of between 40 and 50 tons per sq. in., when drawn through a series of dies, may have its tensile strength increased to 80 to 100 tons per sq. in., although its ductility is reduced considerably; the hardness of the steel is increased as the tensile strength is raised by such mechanical treatment.

It should be mentioned that the hardness and cutting quality of carbon steel increase rapidly as the carbon is increased above 0.85 per cent—corresponding to 100 per cent pearlite—owing to the presence of cementite embedded in the mass.

Mild Steel. Steels containing up to 0.45 to 0.50 per cent carbon are termed mild steels and are widely used for mechanical and structural engineering purposes.

When the percentage of carbon is below about 0.20 the steel cannot be hardened to any appreciable extent by heating to 760° C. to 800° C. (corresponding to a cherry-red heat) and quenching in water; the steel is readily weldable, however.

Steels containing between 0.2 and 0.5 per cent carbon respond to heat-treatment to an increasing extent as the carbon content is increased; such steels can be welded but with rather more difficulty than for iron or lower carbon steels.

Hardening Types of Steels

The carbon steels employed for various kinds of tools, dies, snaps, punches, and for other purposes where suitable hardness and strength properties are desired contain from about 0.6 to 1.5 per cent carbon and respond satisfactorily to heat-treatment. The lower percentage carbon steels are less hard and strong, but are more ductile (or less brittle) than the higher carbon content ones. Steels containing from

about 1.3 to 1.5 per cent carbon give the hardest structures with suitable heat-treatment: such steels are employed for razor blades, extra-hard drills, planing, slotting, and turning tools. High-carbon steels after such heat-treatment are relatively brittle so that they are unsuitable for applications involving appreciable shock or impact effects.

Steel Manufacturing Methods

Steel is manufactured from pig iron, ordinary iron, or iron ores by several methods, the particular process employed depending upon the purpose for which the steel is required. The principal processes by which steel is produced are the (1) Bessemer; (2) Open Hearth; (3) Cementation; and (4) Electric Furnace.

(1) **The Bessemer Process.** In this process the steel is produced from molten pig iron by burning out, or oxidizing, the carbon and silicon. The pig iron is melted in a converter type of furnace mounted on trunnions, and when molten a blast of cold air at a pressure of one to two atmospheres is forced through the molten metal. The combustion of the carbon and silicon with the oxygen of the air raises the temperature of the metal to a white heat value and practically pure iron results. In order to convert this iron into the desired grade of steel, carbon is then introduced in the form of *spügeleisen*—which is a mixture of iron, carbon, and manganese—or ferro-manganese, after the air blast is shut off. When sufficient time has elapsed to enable the molten iron to take up the carbon and manganese the converter is rotated through a suitable angle for the metal to be poured out into moulds to form ingots, the latter are reheated and subjected to mechanical treatment, such as cogging and rolling, to form bars, plates, etc. Since the sulphur and phosphorus of the ore are not removed by the process described it is necessary to keep these elements low in the pig iron employed; usually, not more than 0.05 per cent P and 0.02 per cent S are allowed in the pig iron, so that somewhat similar percentages remain in the resulting steel.

The process described is termed the "acid" Bessemer one on account of the siliceous type of ganister lining used.

The "basic" Bessemer process employs a converter lined with dolomite—which contains carbonates of lime and magnesia. The advantage of this basic lining is that the phosphorus in the molten iron can be removed, by means of an additional blast of air (known as the "after-blow"), after the carbon has been removed. In this way pig iron or iron ores containing appreciable amounts of phosphorus can be employed in producing mild steel.

The Bessemer process has been employed widely for rail and structural steels, but it is now being replaced by the more recent improved open hearth methods.

(2) **The Open Hearth Method.** The original Siemens, or "open hearth," process dates back to 1856 and, in principle, was based upon the removal of the carbon from the pig iron by means of pure iron-oxide ore, such as a special hematite. It employed a reverberatory furnace and used a gaseous fuel. The carbon monoxide formed by the oxidation of the carbon passed away with the flue gases.

In the "acid hearth" process a sand bottom was employed, the iron ore used being very low in phosphorus content.

The later "basic hearth" process resembles the basic Bessemer one in principle and higher percentage phosphorus ores can be used, as the phosphorus is removed in greater part by passing into the slag as calcium phosphate.

The Siemens-Martin open hearth method utilizes scrap iron or steel in place of most of the iron ore, the proportion of scrap iron to pig iron being from 8 to 10 to 1; cast iron mixed with scrap iron and certain fluxes is also employed in this process. The decarburization of the charge is carried out by the oxides formed on the scrap iron, and by adjusting the proportions of the mixture the resulting metal can be arranged to retain the desired proportion of carbon.

Although the open hearth processes are slower than the Bessemer one, they give more uniform results and enable the composition of the steel to be controlled so that the percentage of carbon can be regulated; this is more difficult with the faster Bessemer process. It is principally for this reason that the open hearth method is replacing the Bessemer one for commercial steel production. For steels of higher quality, however, the electric furnace is preferable to either of those mentioned.

Duplex Steel Process. In order to obtain the quick production advantage of the Bessemer process and the more uniform and better quality steel produced by the basic open hearth method, steel is made by a duplex process in which the molten metal from the Bessemer converter is used as a charge for the open hearth furnace. The Bessemer process removes the carbon, silicon, and manganese, whilst the remaining phosphorus and sulphur are eliminated by the basic open hearth furnace.

(3) **The Cementation Process.** In this method steel is produced by adding carbon to wrought iron. Bars of wrought iron, surrounded by charcoal in a fireclay box, are heated to redness for a long period, the carbon gradually penetrating inwards from the outside; the period of

time required to carburize a bar of iron of $\frac{1}{2}$ in diameter is about 36 hours.

For larger sizes and higher percentage of carbon steels the period varies up to 8 or 10 days; thus for spring steels from 6 to 7 days may be required, whilst for high-carbon steel the period may be 10 days. The carbon penetrates the metal from the outside inwards and therefore tends to give the steel a higher carbon content towards the outside. The completion of the cementation process is governed by the results of tests made on trial bars withdrawn from the furnace.

The steel produced by this process is known as *Blister Steel*, owing to its blistered appearance when withdrawn from the furnace. It contains up to 1.5 per cent of carbon and contains a higher carbon content near the surface than in the interior regions. This steel is broken up into pieces about 18 in long, which in turn are bound together with steel wire in bundles, or are piled; the bundles or piles are heated to a welding heat, and forged under a mechanical or steam hammer, and rolled. The resulting product is called *shear Steel*. If the above process be repeated upon this steel it becomes *Double Shear Steel*.

Cast Steel is obtained by melting the broken pieces of blister or shear steel, which are initially produced from a pure brand of wrought iron, and casting into ingots: fireclay crucibles containing graphite are used for the purpose of melting, and each pot usually contains from 40 lb. to 60 lb. of steel. The slag is removed from the surface, and after allowing the metal to stand for a time the latter is poured into ingot moulds. The best grades of cast steel, which are produced from the purest brands of iron, containing only minute quantities of sulphur and phosphorus, after having been obtained in the ingot form, are reheated and rolled into bars, which are then given the name of *Tool Steel*. Both cast and tool steel contain a higher percentage of carbon than the other steels previously mentioned.

(4) **The Electric Furnace.** Both the electric arc and the coreless high-frequency induction types of furnace are used for the manufacture of the highest grades of carbon and also alloy steels.

The electric arc furnace, of which the Héroult and Stassano models are examples, utilizes the heat of the electric arc formed between two electrodes to melt the charge. The arc furnace can be employed either with an acid or basic hearth; the latter type is now more widely used. Special fluxes are introduced to reduce the sulphur and phosphorus so that the resulting steel has very low proportions of these elements. In the electric arc furnace much higher temperatures can be attained than in the Bessemer or open hearth furnaces, whilst the absence of

any oxidizing or carbonizing flame prevents any alteration of the carbon content, this enables iron and steel scrap to be used in estimated proportions to give the required final composition. The basic electric arc furnace is often used for refining steel, i.e. to remove sulphur and to deoxidize the metal from the ordinary basic open hearth furnace.

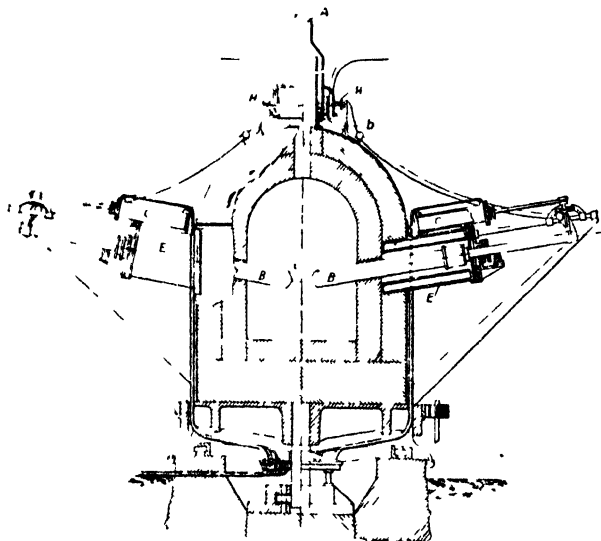


FIG. 63 THE SIASSANO ELECTRIC FURNACE USED FOR STEEL FOR CASTINGS, ETC.

- BB electrodes
- CC hydraulic gear for regulating position of electrodes
- LL water jackets for cooling electrodes
- I funnel for waste gases

The furnaces used for the production of tool steels range from about 3 to 12 tons capacity, the latter size corresponding to 2400 kVA

The $3\frac{1}{2}$ to 4 tons capacity furnace, with 750 kVA transformer, is a popular one for alloy and carbon steels, and for medium-size castings and ingots

In the *Héroult arc furnace* there are no bottom electrodes, so that the lining of the furnace is simpler and can be either acid or basic. The electrodes may either be of amorphous carbon (of about 14 in. diameter) or of graphite (of 8 in. diameter); the electrodes can be seen clearly in Fig. 64.

The furnace is usually arranged on a cradle and roller base, so that it can be hand- or motor-tilted for pouring purposes.

The high-frequency furnace is based upon the heating by induction of the charge contained within the crucible or furnace, by means of a high-frequency alternating current in a special insulated and water-cooled conductor arranged around the crucible. The heat produced varies as the mean square of the current flowing in the conductor and the current strength depends upon the strength of the magnetic

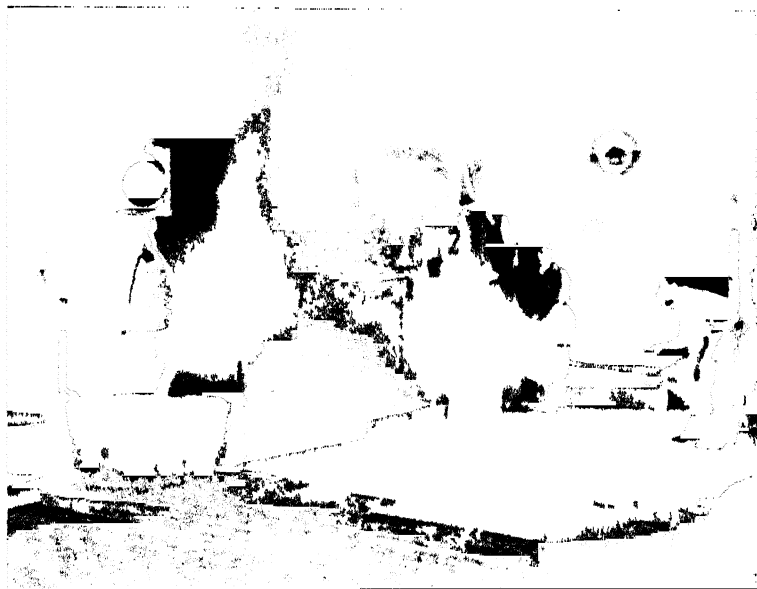


FIG. 64 THE HEROULT ELECTRIC ARC FURNACE
(Edgar Allen Ltd.)

field passing through the crucible charge and to a lesser extent upon the frequency.

This type of furnace enables the ideal shape of crucible or container to be used—namely, a cylindrical one holding a maximum of metal with a minimum of radiating area. Further, the heat is actually generated in the charge to be melted, so that there is a minimum loss of heat as compared with other types of furnace.

There are no furnace gases present with this type of furnace so that no contamination of the charge, or alteration of its composition, need occur. Moreover, the composition of the charge can be selected

to give the desired composition to the final product, since—apart from slight modifications due to degasification of the charge—no other chemical changes occur.

The high-frequency furnace also possesses another important

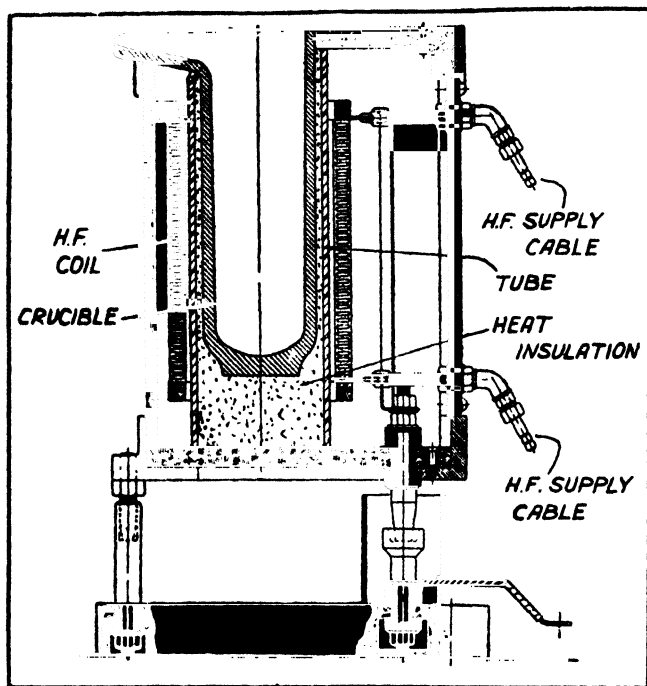


FIG. 65. HIGH FREQUENCY ELECTRIC INDUCTION FURNACE

property, namely, that of promoting a continuous motion in the molten metal, i.e. an automatic stirring action; this is caused by electro-dynamic forces in the charge, due in turn to the inductive effect of the high-frequency current. The principal result of this constant motion is to give a very uniform constitution to the resulting steel; as a result the surface of the molten metal is convex upwards owing to the marked upward movement at the centre of the metal. Yet another advantage is that the temperature of the furnace can be controlled within certain limits, so that uniformity of successive melts is ensured. Fig. 65 illustrates a high-frequency furnace of the coreless

type.* It consists of a container, or crucible, arranged inside a flat cylindrical coil. The intermediate space between coil and crucible, which generally does not exceed 1 in., is filled with zircon or other insulating material contained in a silica or mica sleeve. The crucible or container may be of very thin construction as it fulfils a different

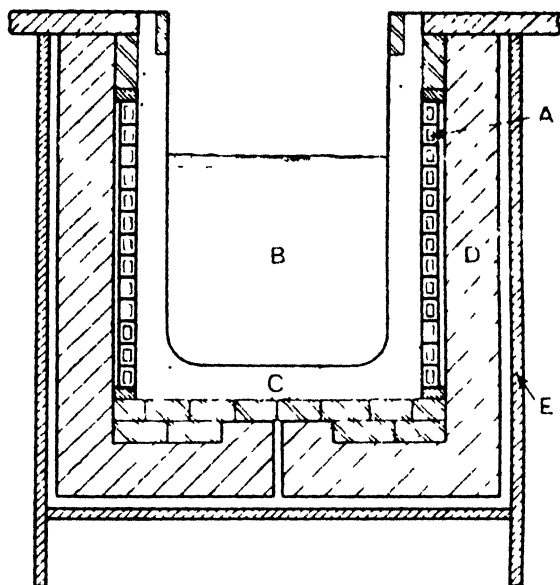


FIG. 66. DIAGRAM OF THE WITTON HIGH-FREQUENCY ELECTRIC FURNACE.

function from an ordinary crucible. If it be $\frac{1}{8}$ in. thick, there is a distance of only $1\frac{1}{8}$ in. between the coil, which is generally water-cooled, and the molten metal, which may be heated to over 2000° C.

The frequency of the alternating current employed varies from about 1000 per second for low-frequency furnaces up to about 20,000 per second for high-frequency ones.

A more recent and improved design of furnace is the "Witton," made by The General Electric Company, Ltd., London. It is based on the Stobie patents.† The fundamental parts of this furnace are shown diagrammatically in Fig. 66, and consist of (1) a spiral water-cooled copper tube inductor coil *A*; (2) the charge to be melted at *B*,

* *The High-frequency Induction Furnace*, D. F. Campbell (*Proc. Iron and Steel Inst.*, 1925).

† *G.E.C. Journal*, Vol. 3, Nos. 2 and 4, pp. 115, 205.

(3) the furnace lining *C*, which acts as a crucible and heat insulator; (4) an external laminated silicon steel core *D*, of high magnetic permeability, consisting of four or more vertical external legs and bottom yokes with a foreshortened central core; this core decreases the reluctance of the external magnetic circuit and thus raises the power factor, and (5) a metal case *E*, which supports the furnace as a whole and enables it to be tilted for pouring, etc. Owing to the skin effect

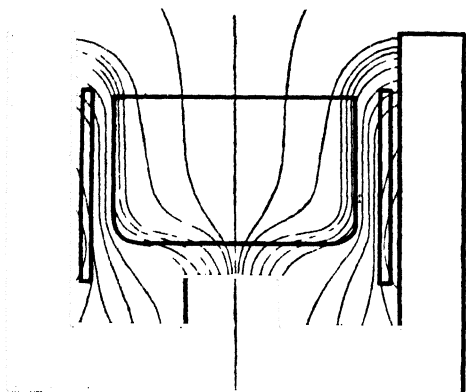


FIG. 67. FLUX DISTRIBUTION IN WITTON HIGH-FREQUENCY FURNACE WITH CHARGE MOLTEN

in both the charge and inductor coil due to the high-frequency current, the current can flow only on the surface of the charge and the inductor, the depth of penetration being a few millimetres only. It will be seen from Fig. 67 that the flux produced by the inductor in effect interlinks with a thin cylinder of metal of comparatively high resistance, causing a current to flow round the cylinder, thus raising its temperature. The particular furnace described has a capacity of $\frac{1}{2}$ ton, is rated at 150 kW for a melting period of 2-2½ hours, and operates at 1000 cycles per second with a supply voltage of 1200. It is employed for high-grade carbon and alloy steels, including stainless and heat-resisting steels, etc. This type of high-frequency furnace is more efficient than most other types previously used and enables appreciable economies to be effected in steel production.

Effects of Manganese, Silicon, Phosphorus, and Sulphur

Since all plain carbon steels usually contain small percentages of these elements it is necessary to know what effect these elements have upon the physical and mechanical properties.

Manganese in small quantities up to about 1 per cent appears to behave in the same way as carbon in its effects upon the hardness and strength of the steel. It tends to reduce the oxygen content and largely counteracts the effect of the sulphur in the steel. From 0.3 to 0.9 per cent is usually present in steel.

Silicon, when present in limited amounts, tends to make the steel harder and stronger, but at the expense of reduced ductility. It has good deoxidizing qualities and renders the metal sounder, i.e. freer from included gases, such as oxygen and carbon monoxide. Silicon reduces the temperature of fusion and prevents blow-holes; it tends, however, to increase the size of the grain. In steel castings from 0.2 to 0.5 per cent of silicon is employed for producing sounder and stronger results. The addition of silicon to steel increases its electrical resistance, and is useful for steel employed for the cores of electromagnets. The usual amount of silicon in low- and medium-carbon steel ranges from 0.10 to 0.30 per cent.

Phosphorus is kept low in steel. It tends to increase the strength, hardness and fluidity but reduces its resistance to impact effects and with ordinary heating gives larger grain size. Usually from 0.04 to 0.08 per cent is employed.

Sulphur above about 0.50 per cent makes the steel brittle and "red short"; it promotes oxidation. The effect of sulphur can be to some extent counteracted by the inclusion of about twice its percentage of manganese. The maximum sulphur content allowed in most steels is about 0.05 per cent.

The Hardening of Steels

Disregarding the method of increasing the hardness of a steel by work-hardening processes such as cold-rolling, steel containing more than about 0.2 per cent carbon can be hardened by heating it to a temperature above its upper critical point and cooling it more or less rapidly in a suitable medium such as water, oil, or air. In general the quicker the cooling rate the harder and more brittle will the steel become; the slower the cooling the softer and more ductile.

Whilst the general effects of rapid cooling of steels have previously been considered the results may be summarized, briefly, by stating that the effect of quenching or otherwise cooling the steel rapidly from a temperature above the critical range is to arrest the transitional products or to retain the solid solution state so that in the case of medium- and high-carbon steels, instead of allowing the pearlite and ferrite to remain, other constituents such as martensite, austenite, troostite, and sorbite are retained at normal air temperatures. When

steel exists in the quenched state, the presence of these constituents increases the strength and hardness but reduces the ductility.

The correct quenching temperature for hardening is that at which there is a homogeneous solid solution, the temperatures in question vary with the grade of carbon or alloy steel. For plain carbon steels the quenching temperature increases with a reduction in carbon content, thus for a 0.25 per cent carbon steel the temperature was 875° C., this value falling to 830° C. for one of 0.75 per cent carbon. In this connection the actual temperatures also depend to some extent upon the other elements present and their proportions.

The constitution of a hardened steel is dependent also upon the actual quenching temperature, as it is possible to employ a range of temperatures above the lower arrest points. The results of some tests made upon carbon steels of 0.09 to 2.5 per cent carbon, when quenched at a rapid rate above or between the Ar. 1, Ar. 2, and Ar. 3 points, are given in Table 25, which shows the relative volumes of the constituents in the steel. It will be observed that as the quenching temperature of the 0.09 per cent carbon steel is reduced the proportion of ferrite increases and that of martensite diminishes.

For the 0.21 to 0.35 per cent carbon steel the martensite is reduced with reduction of quenching temperature and ferrite appears for temperatures between the Ar. 2 and Ar. 1 points.

For steels with more than 0.80 per cent carbon there is no ferrite for any of the quenching temperatures, but there is a tendency for the martensite to diminish and the cementite to increase with a lowering of the quenching temperature.

Annealing, Normalizing, and Spheroidizing Steels

Annealing is the term used for the process of reheating a steel to a temperature of not more than 50° C. above the Ac. 3 point, in the iron-carbide diagram, and then allowing it to *cool slowly* in the furnace or in a bath of sand or fine ashes. According to the British Standards Institution definition, *Annealing means reheating followed by slow cooling and its purposes may be to remove internal stresses or to induce softness, in which case the maximum temperature may be arbitrarily chosen.* It may be employed to refine the crystalline structure as well, in which case the temperature must not exceed the upper critical range as in normalizing.

Annealing results in a softer but coarser structure than that obtained by the normalizing process, but whereas these two methods give similar tensile strengths and percentage elongations, normalizing gives a greater percentage reduction of area in most instances.

Annealing occupies a longer period than normalizing and is applied to castings, forgings, multi-stage pressings, spinings, etc., to remove casting or work-produced stresses and render the metal in the soft and ductile condition.

Normalizing consists in heating the steel to a temperature above its upper critical point and then allowing it to cool in the air—which should not be in motion, since draughts tend to cause unequal cooling and therefore internal stresses. According to the British Engineering Standards definition: *Normalizing means heating a steel (however previously treated) to a temperature exceeding its upper critical range and allowing it to cool freely in the air. It is desirable that the temperature shall be maintained for about 15 minutes and shall not exceed the upper limit of the critical range by more than 50 °C.*

Either annealing or normalizing work-hardened steel, such as rolled sheet and rod, reduces the tensile strength but increases the ductility, as shown by the elongation and reduction of area values. The strength properties of 0.13 and 0.25 per cent carbon steels in the rolled, annealed, and normalized conditions (for the periods of heating at the specified temperatures) are shown in Table 26.

TABLE 26
EFFECT OF ANNEALING AND NORMALIZING CARBON STEEL
ROLLED BARS. (Harbord)

Type of Steel and Condition	Period of Process, Hours	Yield Point, Tons per sq. in.	Tensile Strength, Tons per sq. in.	Elongation per cent in 2 in.	Reduction of Area per cent
0.13 per cent carbon					
As rolled			30.20	20.0	34.70
Annealed at 720 °C.	$\frac{1}{2}$	11.34	20.16	44.5	73.26
Annealed at 800 °C.	$\frac{1}{2}$	10.20	20.10	46.0	71.16
Normalized at 900 °C.	$\frac{1}{2}$	13.00	21.50	45.0	71.16
Annealed at 720 °C.	12	11.60	20.00	42.5	73.20
0.25 per cent carbon:					
As rolled			33.2	12.7	25.3
Annealed at 620 °C.	$\frac{1}{2}$	27.80	34.5	24.0	55.0
Annealed at 720 °C.	$\frac{1}{2}$	18.24	28.8	32.5	62.6
Annealed at 800 °C.	$\frac{1}{2}$	19.40	29.4	29.5	58.6
Normalized at 900 °C.	$\frac{1}{2}$	17.28	29.4	32.5	54.8
Normalized at 1100 °C.	$\frac{1}{2}$	15.30	28.1	33.5	54.7
Annealed at 620 °C.	12	14.30	26.8	32.5	71.4
Annealed at 720 °C.	12	15.80	28.2	31.0	57.3
Annealed at 900 °C.	12	25.10	29.5	29.0	57.5

Spheroidizing, a process also known as *sub-critical annealing*, is the term applied to the method of heating the steel for a prolonged period at a temperature below the lower critical point—usually between 670° and 680° C. The result of this treatment is that the iron carbide becomes transformed into spheroids or balls of minute size, embedded in a matrix of almost pure iron in the soft state. Steel in this condition is able to withstand considerable deformation by cold working, e.g. cold rolling or cold pressing, although for the latter purpose normalizing is a quicker and more economical operation giving fully satisfactory results.

Annealing Processes

The objects to be annealed should be heated slowly in a closed furnace or muffle, free from draughts, until the correct annealing temperature is attained, the temperature should be kept uniform for several hours, the exact time depending upon the size and steel composition.

Small low-carbon steel objects when annealed in a box take from one to three hours; large alloy steel articles from three to eight hours.

At the termination of the annealing period, the objects should be allowed to cool down very slowly either by (a) shutting off the furnace heat supply, and allowing the whole to cool naturally, or (b) burying the objects taken from the furnace in fine ashes, dry sand, sawdust, or lime, and allowing them to cool.

Method (a) is the better, when it can be conveniently employed, as it excludes the possibility of too rapid initial cooling and of uneven cooling due to draughts when withdrawing from the furnace to the cooling medium as in case (b).

It is of great importance not to heat the steel to too high a temperature, or too rapidly, otherwise the grain will be coarse.

The period required for annealing steel castings usually varies from 16 to 32 hours, and for malleable iron from 60 to 120 hours, the temperature of annealing being 900° C. to 950° C. for the Réaumur process, and 800° C. to 850° C. for the black-heart type of malleable iron.

Box Annealing. The recommended method of annealing small and medium steel objects is that known as the "box annealing" method, in which the parts are placed in a steel plate, or cast-iron, box lined with firebrick, and the whole gradually heated to the annealing temperature; after the stipulated period they are allowed to cool slowly.

In all cases of annealing steel objects, care should be taken to prevent the access of air to the heated parts, otherwise surface oxidation or decarbonization will occur. In box annealing, the edges and

openings of the box should be filled up with fireclay, and in many cases it has been found advantageous to fill the empty space in the annealing box with sand, fireclay, slaked lime, fine ashes, or charcoal; alternatively a little resin placed in the box is effective, and the other materials mentioned need not then be used.

When using cast-iron boxes it is essential to prevent the steel objects from coming into direct contact with the sides of the box, as cast iron has a great affinity for carbon, and will therefore tend to decarbonize the steel; where such boxes are used, a layer of charcoal or lime, or a lining of firebricks, must be used.

A quick annealing process consists in heating the steel to a red heat (750 °C to 800 °C) an hour or so, then placing it in dry sand, lime, sawdust, or fine ashes, well covering it, thus allowing it to cool slowly.

Many objects can be conveniently annealed by heating them in a molten salt or alloy bath and allowing them to cool in sawdust.

Handling of Heated Objects. When heated objects are removed

TABLE 27
ANNEALING TEMPERATURES FOR TOOL STEELS

Type of Steel	Temperature of Annealing		Period	Remarks
	Cent	Fah	Hours	
No. 1 Temper, $1\frac{1}{2}$ per cent carbon	720	1328	1 to 4	These temperatures should not be exceeded, and tools should be box annealed.
No. 2 Temper, $1\frac{1}{4}$ per cent carbon	720	1328	1 to 4	
No. 3 Temper, $1\frac{1}{8}$ per cent carbon	720	1328	1 to 4	
No. 4 Temper, 1 per cent carbon	720	1328	1 to 4	
No. 5 Temper, $\frac{7}{8}$ per cent carbon	750	1382	1 to 4	
No. 6 Temper, $\frac{1}{2}$ per cent carbon	770	1418	1 to 4	
<i>High speed Tool Steel</i>				
Tungsten 8 to 18 per cent, Chromium 4 to $5\frac{1}{2}$ per cent	870	1600	2 to 3	Heat slowly so that tools take from 1 to 2 hours to attain annealing temperature, then keep at same for 2 to 3 hours, and allow to cool in furnace, or bury in fire ashes, lime, dry sand, etc.
Carbon 1.8 to 0.7 per cent, Vanadium 0 to 0.29 per cent	930	1700	2 to 3	

from the hardening or annealing ovens, they should be gripped with *heated tongs*, otherwise local cracks and hardness variations are apt to occur; the tongs, or grips, should be heated at least to a black heat (350°C to 400°C .)

Annealing Tool Steels The annealing temperatures and periods

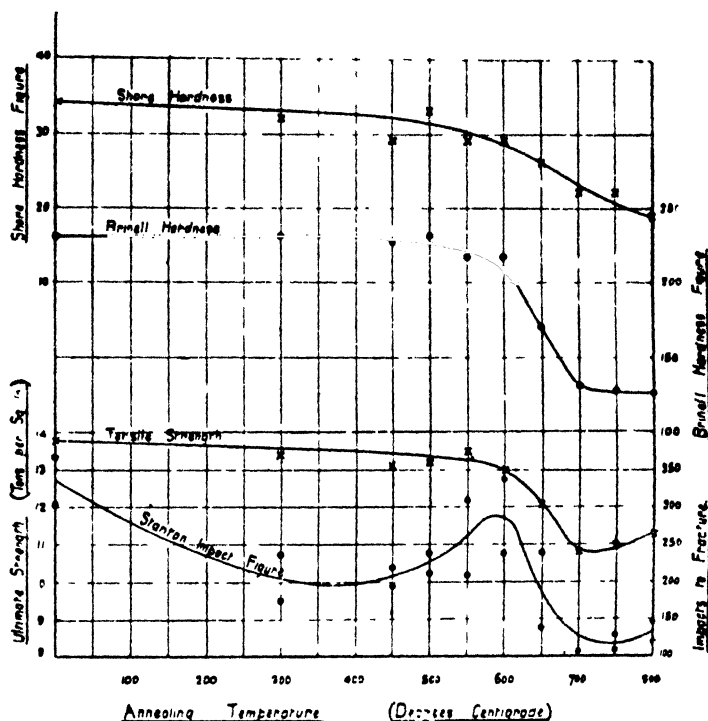


FIG. 68. ANNEALING TEMPERATURES AND MECHANICAL PROPERTIES OF CAST IRON FOR AUTOMOBILE WORK

vary with the composition and it is not possible, therefore, to give information that will be applicable generally. In all instances the steel manufacturer's instructions for the grade of tool steel supplied should be followed.

The annealing temperatures for some typical carbon tool steels and two alloy ones, given in Table 27, will afford an indication of the range of temperatures employed.

Annealing of Cast Iron. The results shown graphically in Fig. 68 illustrate the effect of annealing cast iron, such as that used for petrol

engine pistons at different temperatures. Apart from the beneficial effects of annealing, in removing casting stresses, and in improving the structure, it will be seen that up to about 500° C. there is practically the same tensile strength and hardness, but that the impact value is markedly affected. From above about 600° C. the strength and hardness are seriously diminished.

Pearlitic grey cast iron is fully annealed in the temperature range of 800 to 900° C. for a short time in order to obtain rapid machining qualities, although there is a general loss of strength and hardness. For the purpose of relieving stress this quality iron is annealed by heating slowly to 450 to 550° C. and holding the parts corresponding to about one hour per inch of section thickness, followed by slow cooling. This method is employed for castings and not only relieves stresses due to casting but also in many instances, gives improved tensile strength and toughness.

Local Annealing of Hardened Parts

Hardened steel parts, such as case-hardened articles, Harveyized* nickel or carbon steel plate, etc., may be softened locally by heating the place with an electric arc or oxy-hydrogen flame, and allowing it to cool as slowly as possible.

Armour plates with chilled surfaces are softened in this way for drilling purposes.

Classification of Carbon Steels

There is a wide range of carbon steels employed in engineering work, from the dead mild low carbon grade up to the high-carbon steels (0.6 to 1.4 per cent C) used for cutting and press tools of various kinds. Most steel manufacturers, however, produce definite grades with increasing carbon content usually based upon the British Standards Institution and Air Ministry Specifications for aircraft, automobile, and general engineering purposes. A typical instance of this practice is that adopted by Messrs. Firth & Brown Ltd., who have standardized the grades of carbon steels given in Table 28, from 0.2 to 0.75 per cent carbon and 25 to 60 tons per sq. in. tensile strength for engineering purposes, as distinct from the high-carbon cutting steels.

The steels in question are usually employed in the normalized or annealed condition, although the properties of the higher carbon

* The process of Harveyizing steel plate consists in covering it with carbonaceous material and heating to 850° to 950° for about 120 hours, followed by water jet quenching.

TABLE 28

PROPERTIES OF CARBON STEELS FOR ENGINEERING PURPOSES

Steel No.	Typical Analysis			Heat treatment	Tensile Mechanical Properties on 1-in. dia. Bar			
	Carbon per cent	Silicon per cent	Manganese per cent		Min. strength tens per sq in.	Yield Point tens per sq in.	Elongation per cent	Red. of Area per cent
C 40	0.20	0.25	0.60	Normalized 900 ° F	28	15	35	55
C 41	0.30	0.25	0.60	Normalized 870 ° F	32	17	31	50
C 42	0.40	0.25	0.60	Oil H 870 ° F 750-670 ° F	36	24	30	45
C 43	0.50	0.25	0.60	Normalized 850 ° F	40	21	26	45
C 44	0.55	0.25	0.60	Oil H 850 ° F 750-650 ° F	43	27	25	40
C 45	0.75	0.25	0.60	Normalized 840 ° F	47	29	22	35
				Oil H 840 ° F 750-650 ° F	50	27	18	45
				Normalized 800-820 ° F	55	31	14	25

content steels are much improved by oil-hardening (O.H.) and tempering, and such steels are often employed in this condition.

Forging of such steels should be carried out at temperatures not exceeding 1200 °C. (lemon-white heat) for the lower carbon steels, and 1150 °C. (lemon heat) for steels of 0.5 per cent carbon upwards.

Machining of these steels is carried out in the normalized and sometimes in the oil-hardened and tempered condition; the steels in question are supplied in either of these conditions by the manufacturers. For forgings and drop-stampings the steel should always be heat-treated in the prescribed manner before machining or putting into service, in order that the best mechanical properties can be developed.

Table 29 illustrates some typical applications of the steels given in Table 28.

TABLE 29
APPLICATIONS OF CARBON STEELS

Carbon per cent	Applications
0.20	For all kinds of lightly stressed machine fittings, stampings, and pressings used in aircraft, automobile, and general engineering. This steel is supplied in rod, bar, tube, plate, and wire.
0.30	For machined fittings, stampings, and pressings of higher strength
0.40	For spindles, axles, gears, keys, machined fittings, pressings, and stampings requiring good strength properties and wear resistance.
0.50	For more heavily stressed working parts in aircraft and automobile construction and in general engineering work
0.55	For forgings and stampings required to resist wear, e.g. cylinder liners for engines, hammers, boiler makers' and miners' tools, etc.
0.75	For clutch plates and springs, blacksmiths' tools, cold shear blades,

Steel Castings

Castings made of steel are stronger and more ductile than those of the ordinary cast irons and are much used for engine and machinery parts that have to withstand heavy loading or shock effects. The present considerations relate to carbon-steel castings but it should be mentioned that there are stronger and tougher steels containing elements such as chromium, vanadium, titanium, and manganese, to some of which reference is made later in this book.

The steel used for castings for various purposes has a carbon content

up to 0.90 per cent. In the case of automobile steel castings a typical percentage composition is as follows: C, 0.30 to 0.40, Mn, 0.50 to 0.80, Si, 0.10 to 0.30, P and S not over 0.05 each; Fe, the remainder. In the annealed condition the elastic limit of this steel is about 16 tons per sq. in.

The *general-purpose steels* for castings contain 0.2 to 0.35 per cent carbon and possess tensile strengths of 27 to 35 tons per sq. in. with elongations of 20 to 30 per cent and reductions of area of 20 to 40 per cent. To develop the full strength properties the castings should be given an appropriate heat-treatment corresponding to their composition, mass, etc.

The *low-carbon steels* for castings with less than 0.2 per cent carbon do not respond appreciably to heat-treatment in regard to their strength properties, but the grain structure and ductility are improved by suitable heat-treatment. The tensile strengths of this class of steels range from 18 to 32 tons per sq. in., with elongations of the order of 15 to 30 per cent. Owing to their low carbon content the castings are suitable for electrical purposes but not, in general, for structural work.

The *high-carbon steels* for castings contain from 0.4 to 0.9 per cent and respond much better to heat-treatment than the other steels mentioned previously. In suitably heat-treated condition these steels possess tensile strengths of 35 to over 50 tons per sq. in., with 3 to 20 per cent elongation and 8 to 40 per cent reduction of area. Such steels are employed for engineering purposes where high strength and toughness properties are required, e.g. for automobile parts, roll and die tool parts, railway and marine equipment.

The British Standard Specification (B.S.S. 592—1935) covers three grades of steel castings, namely, 26, 28, and 35 tons per sq. in. The steel used is preferably made by the open hearth process, acid or basic, and the maximum allowable sulphur and phosphorus contents must not exceed 0.06 per cent each. The castings should be heat-treated to refine the crystalline structure throughout by heating to a uniform temperature not less than the normalizing temperature and allowing to cool slowly. The tensile test properties are specified in Table 30.

Cold bend tests, specified for these steels, are to be made upon test pieces 9 in. long of 1 in. diameter or $9 \times 1 \times \frac{3}{4}$ in. rectangular section, the tests being made by bending over the thinner section round a former of 1 in. radius. The test pieces must withstand such bending for angles of bend of 60°, 120°, and 90° for the 35, 28, and 26 tons per sq. in. grades respectively, without fracture. It is further specified that the castings are to be hammered to ensure that they are sound and flawless.

TABLE 30
BRITISH STANDARD STEEL CASTINGS

Grade of Casting	Tensile Strength Tons per sq. in.	Yield Point Tons per sq. in.	Elongation per cent
26	26	13	20
28	28	14	20
35	35	17.5	15

Steel castings are produced in crucibles, converters, open hearth furnaces, and electric furnaces, the two latter methods being the most favoured. acid or basic linings are employed in these latter methods. The raw materials used include iron ore, steel scrap, and pig iron, the actual selection and proportion depending upon the type of furnace and the desired composition. For alloy casting steels the electric induction furnaces are preferred.

Steel castings for engineering purposes range from those of $\frac{1}{4}$ in. thick weighing a few ounces to very many tons and in sections up to 4 ft. thick. Thus, the largest steel castings made by The English Steel Corporation include examples up to 150 tons. Typical castings made by this firm include an 85-ton steel baseplate for a hydraulic press (Fig. 69) and two 120-ton baseplate main girders for a hydraulic press each measuring 32 ft. long, 11 ft. 3 in. deep, and 5 ft. 6 in. wide.

Applications Steel castings (plain and alloy) are employed for a variety of purposes, typical instances being those for electric motor yokes, marine cylinder frames, mill housings, press castings, hydraulic cylinders, gears, mill rolls, rear axle casings for heavy lorries, axle boxes, buffer casings and other parts for locomotives and railway carriages, turbine casings, magnet frames, armature and commutator hubs and spiders, hydraulic stay rings, manganese steel crusher jaws and liners for cement mills, autoclaves, cast steel dredger buckets and tumblers, mortar boxes, stamper heads, and other mining machinery parts.

Notes on Steel Castings

Steel castings are made from steels having melting points of about 1350° to 1400° , whilst cast irons have appreciably lower values, namely, 1050° to 1250° . The amount of cooling contraction is therefore greater for steel castings than for cast-iron ones. It is usual to allow about $\frac{3}{2}$ to $\frac{3}{4}$ in. per ft. shrinkage for steel and $\frac{1}{4}$ in. per ft. for cast iron for normal sizes and shapes.

The annealing temperatures range from 830 °C for carbon contents of 0.55 to 0.80 per cent up to 925 °C for 0.16 per cent carbon.

Semi-steel

This name is usually given to the product resulting from the addition of steel and wrought iron scrap to cast iron in the cupola.

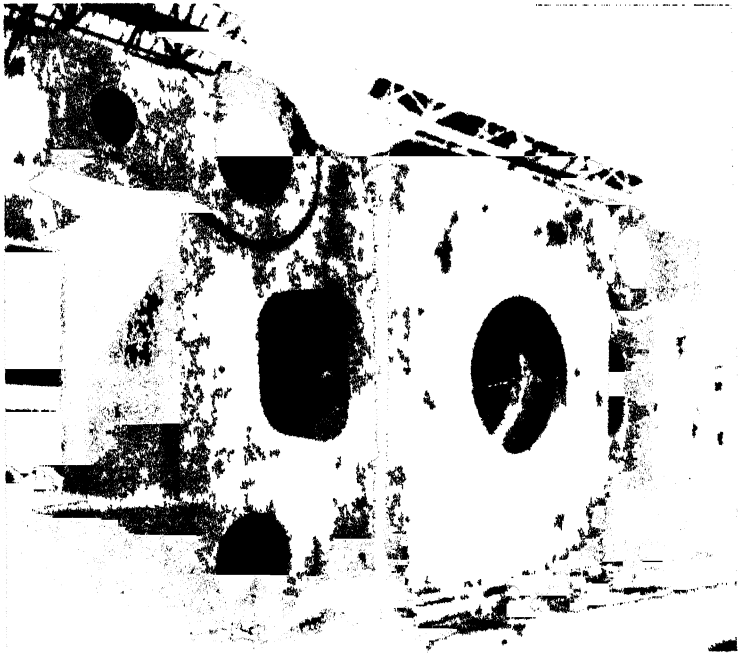


FIG. 69. CAST STEEL BASEPLATE WEIGHING 8½ TONS FOR HYDRAULIC PRESS (English Steel Corporation, Sheffield)

usually about 20 to 40 per cent scrap is thus added. The semi-steel thus produced has less carbon than ordinary cast iron, namely, below 3 per cent. It is stronger and tougher than ordinary cast iron and has a finer grain, although it belongs to the true cast iron class.

Semi-steel has been used for making the tables, slides, saddles, etc., of machine tools and for large gears.

Carbon Tool Steels

These steels are usually produced in the electric furnace, notably the high-frequency induction type, so that there is no contamination

by flue gases, etc. a high-grade fine-structure steel results! Although such steels are not so efficient in cutting action and durability as high-speed alloy steels, they are cheaper and for a large number of purposes are entirely satisfactory. In general, carbon steel tools fail at a much lower cutting temperature than high-speed steel ones, so that in selecting high-duty tool steels this point should be borne in mind. Thus if the work to be performed by the tool is such that not much heat is developed, e.g. in rock-drilling, blacksmiths' work, engineers' files, chisels and hammers, a carbon steel is quite satisfactory.

Special care is taken in the manufacture of carbon tool steels to avoid defects, such as gas inclusions, clinks, segregation, piping, etc. As an instance of this case, mention may be made of the practice of a well-known firm of steel manufacturers, Messrs. Edgar Allen Ltd., of breaking off the top end of each ingot produced in the electric furnace. These "ends" are examined for defects. The tendency of an ingot, after being cast, is to develop a "pipe" at the top due to contraction in cooling, the outside cooling more rapidly than the centre. The top is also liable to become honeycombed with bubbles of occluded gases. After the ingots have been rolled or hammered into what are known as "cogged" bars, the ends of these bars are again broken off and the fractures examined. Finally, the finished bars have their ends broken off and the fractures are carefully examined for defects. Mechanical strength tests, chemical analyses, and microscopical examination of the metal are also made upon selected samples.

It is difficult to standardize the numerous carbon steels required for the less expensive types of tools on account of the wide variations in hardness and cutting action and general desirable qualities, so that it is the custom of each steel manufacturer to employ his own system of grading such steels; in such cases some of the steels are usually selected to conform to certain existing standards, such as those of the British Standards Institution. A typical instance of the method of grading carbon tool steels, namely, that employed by Messrs. Edgar Allen Ltd., Sheffield, consists in standardizing six qualities of steels, each of which is supplied in six different grades of hardness or temper. The qualities are distinguished by the letters *H*, *P*, *E*, *C*, *V*, and *F*, the former being the highest quality, and the hardnesses or tempers by numbers from 1 to 6, the former being the hardest steel. The temper numbers actually correspond to the carbon content.

Table 31 shows the carbon contents and the recommended applications of the steels.

Steel Colours and Temperatures. Although in modern forging and heat-treatment practice the temperatures of the furnaces and

TABLE 31

CARBON TOOL STEEL COMPOSITIONS AND APPLICATIONS

Temper Number	Carbon per cent	Applications
1	1.35	Suitable for extra-hard planing, slotting, and turning tools, drills, etc.
2	1.20	Suitable for lathe tools, drills, and small cutters.
3	1.05	Suitable for large turning tools, cutters, taps, reamers, drills, punches, blanking tools, etc.
4	0.90	Suitable for cold chisels, blades for hot shearing, hot setts, taps, special miners' drills, etc.
5	0.75	Suitable for chisels, setts, blue smiths' tools, blades for cold shearing, etc.
6	0.60	Suitable for boiler makers' tools, hammers, miners' tools, etc.

heat-treatment salt or metal baths are invariably measured with accurate pyrometers, it occasionally is necessary to obtain an indication of the approximate temperatures of heated steel by observation of its colour. In this connection Table 32, showing the colours and equivalent temperatures, may be found useful.

TABLE 32

STEEL COLOURS AND TEMPERATURES

Colour of Heated Steel	Temperature °C.
Dazzling slightly bluish white	1600
Brilliant white	1500
White welding heat	1400
Yellow-white	1300
Orange-yellow	1200
Orange-red	1100
Bright cherry-red	1000
Cherry-red	900
Dull cherry red	800
Dark heat	700
Red heat, just visible in sunlight	580
Red heat, visible in daylight	525
Red heat, visible in twilight	475
Red heat, visible in the dark	400

[Machinery]

Forging Carbon Tool Steels. The steels with carbon contents up to 0.90 should be heated slowly and evenly to a bright red heat (950° C.)

for forging, whilst the higher content steels, from 1.0 to 1.40 per cent carbon, should be forged at a cherry-red heat (900°–950° C.).

Normalizing Carbon Tool Steels. This process should be carried out before machining or after forging and before hardening. Steels with 1.2 to 1.4 per cent carbon are normalized at 840° to 860° C.; those with 0.90 to 1.1 per cent carbon at 800° to 820° C.; and for 0.50 to 0.80 per cent carbon, 800° to 830° C. After soaking at these temperatures the steels should cool off freely in air.

Hardening Carbon Tool Steels. The steels should be reheated slowly and uniformly to the temperatures shown in Table 33.

TABLE 33
HARDENING TEMPERATURES FOR CARBON STEELS

Percentage of carbon .	1.20 1.40	0.95 1.05	0.85 0.90	0.60 0.80
Temperature °C	760 780	760 800	780 800	800 820

The steel should be quenched in water, but a good practice is, when quenching, not to allow the steel temperature to fall below the boiling-point of water and then immediately to follow with the tempering operation.

A hardened tool can be relieved of its hardening strains by immersing for a period in a bath of boiling water; its hardness will not be affected adversely by this process.

The Tempering Process

The object of this process is to reduce the extreme hardness of the steel as quenched from the hardening temperature in order to reduce the brittleness and improve the shock-resisting qualities.

The following is the British Engineering Standards Association's definition of tempering: "*Tempering means heating a steel (however previously hardened) to a temperature not exceeding its carbon change point with the object of reducing the hardness or increasing the toughness to a greater or less degree.*"

The operation may usually be followed either by slow cooling or water-quenching without materially affecting the final result.

The effect of tempering a hardened steel is to break down the hardened state of steel, and to transform the "hardening" constituents into others corresponding to the softer conditions. Thus, instead of being entirely composed of austenite, martensite, and troostite it contains also sorbite, pearlite, and ferrite in proportions depending upon the reheating temperature. It should be remembered that the higher the

tempering temperature, the more unstable become the transition constituents, until at the critical change points complete instability or breakdown occurs, leaving the metal in its softest condition.

Table 34 shows the effect upon the constitution of the metal of tempering 1.57 per cent carbon steel at different temperatures, it was found that the heating curve of this steel showed three accelerations, namely, at 275 °C., 400 °C. to 500 °C., and 610 °C. to 700 °C., so that the tempering temperatures were chosen accordingly.

TABLE 34
EFFECT OF TEMPERING UPON THE CONSTITUENTS OF 1.57
CARBON STEEL (Osmond)

Method of Heat treatment	Tempering Colour	Condition of Structure
Quenched from 1050 °C. in ice water		Austenite with smaller amount of hardenite present as barbed streaks or laminae, which cannot be scratched with a needle.
Quenched from 1050 °C., and tempered at 275 °C.	Pale yellow	Austenite and hardenite; the latter can be slightly scratched with a needle.
Quenched from 1050 °C., and tempered at 395 °C.	Blue	Austenite and hardenite; both can be readily scratched with needle. Austenite residue covered with numerous spots and cleavages, parallel to needles of hardenite; greater proportion of latter.
Quenched from 1050 °C., and tempered at 495 °C.	Dark blue	Martensite and troostite with cementite.
Quenched from 1050 °C., and tempered at 620 °C.		Chiefly sorbite and cementite.
Annealed		Cementite and pearlite

The Tempering Process in Practice The methods of tempering hardened carbon steel used in practice depend either upon the use of temperature-controlled reheating media or upon the observation of the oxide colours which form upon polished hardened steel when it is reheated to different temperatures. These colours range from dark blue up to pale yellow and each colour is associated with a definite temperature, the dark blue being the highest and pale yellow the lowest temperature; thus, reheating to the former colour temperature gives the softest and to the latter temperature the hardest temper, but more brittleness and lower shock-resistance qualities.

Table 35 gives the temper colours and corresponding temperatures;

it also indicates the applications of the different tempers to typical tools.

TABLE 35
TEMPERING COLOURS, TEMPERATURES, AND APPLICATIONS

Tint of Oxide on Surface of Steel	Centigrade	Fahrenheit	Suitable for
Dark blue	316	600	Hand saws.
Blue	293	560	Fine saw-blades, augers, boiler-makers' snaps, chisels, smiths' tools and cold sets.
Bright blue	288	550	Watch-springs, swords.
Purple	277	530	Table knives, large shears and wood-turning tools.
Brown, beginning to show purple	266	510	Axes, planes, and wood-working tools.
Brown	254	490	Scissors, shears, cold chisels, large drills, shear-blades, punches, and wood-cutting tools.
Golden yellow	243	470	Penknives, hammers, taps, reamers, large lathes, planing, and slotting tools, small drills, screwing, stamping, and cutting dies and miners' drills.
Straw	230	446	Razor blades.
Pale yellow	221	430	Small edge tools, small lathes, planing, and slotting tools.

[Edgar Allen Ltd.]

Electrical Heat-treatment Salt Bath

A typical electrically heated salt bath installation is shown in Fig. 70. It is employed for the hardening of high-speed steel tools without any risk of oxidation or decarburization; also for the brazing of high-speed steel tips on to tools and cutters. The salt bath furnace obviates the necessity of using a neutral gas atmosphere for these processes.

The furnace is made in the 30 kW and 70 kW sizes with salt bath dimensions of 8 in. diameter \times 12 in. deep and 12 in. diameter \times 18 in. deep respectively. It works on a 3-phase supply and has a maximum operating temperature of 1400 °C.

The main electrodes are carried in the inner refractory lining and extended to convenient positions for connection to the transformer. Suitable auxiliary starting electrodes are also provided. Provision

for time extraction is made by means of a fan driven by a $\frac{1}{2}$ h.p. squirrel cage 3-phase induction motor. The transformer is connected to the furnace by means of heavy copper busbars and is the double wound oil-immersed type suitable for a primary voltage of 400 or 440 volts 3-phase 50 cycles with a series of tapplings on the high tension side to give the low secondary voltages required for the furnace.

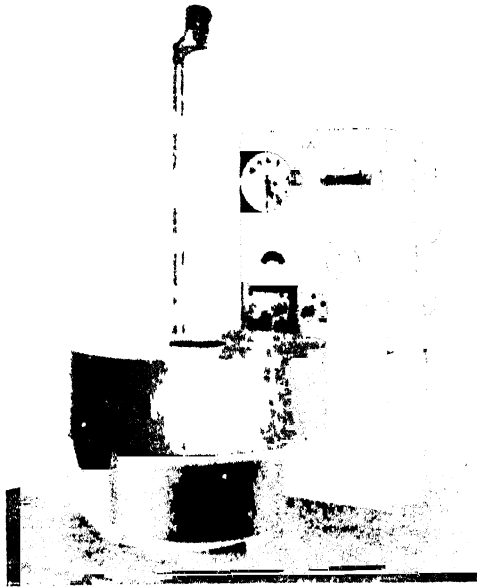


FIG. 70. THE G.E.C. ELECTRICAL HEAT TREATMENT SALT BATH.

An instrument panel carries a temperature indicator, synchronous electric clock, one isolating switch for the clock and one for the ammeter which gives readings on the secondary side of the transformer. An on load tap changing switch is built into the transformer and a radiation type pyrometer is provided to give an indication of the bath temperature.

Workshop Tempering Methods

The method employed in engineering workshops for hardening carbon steel edge or end tools consists in heating the end of the tool to the

proper hardening temperature and then dipping this end into water. Afterwards—and before the steel has cooled down too much—it is quickly withdrawn and the metal near the end to be tempered is cleaned with a piece of emery cloth or bath brick in order to reveal the tempering colours. The latter will be observed travelling towards the cooled end, the pale yellow colour being the first to approach and the dark blue the last. When the appropriate colour reaches the end of

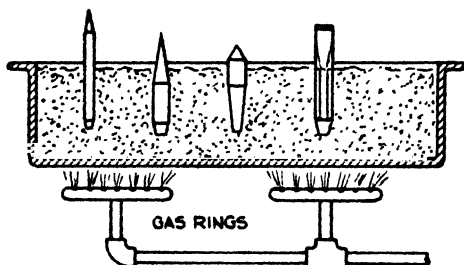


FIG. 71. METHOD OF TEMPERING EDGE OR END TOOLS
IN A SAND BATH

the tool the latter is quenched out in cold water. Alternatively, the articles can be tempered in a sand bath as shown in Fig. 71.

In the case of articles such as dies and milling cutters, which have to be of equal temper throughout, these are first hardened right out and then tempered by reheating in a sand bath or over a plate heated from below. As soon as the desired colour is attained, the articles are quenched in water. Carbon steels can also be *tempered in a single operation* by heating to the appropriate hardening temperature* and quenching in a suitable medium, such as oil, which will give the correct rate of cooling. Various grades of hardening oils are now supplied commercially to give different cooling rates and therefore different degrees of hardness.

Melted lead or lead-tin alloy is also employed for articles requiring less hardness than that given by the oil bath. In this connection lead melts at 327° C. and tin at 232° C., so that by suitably selecting the proportions of lead to tin any desired quenching temperature can be obtained, down to the eutectic melting point, namely, 180° C.

Lead-antimony alloys give a temperature range of 228° C. to 630° C., the latter temperature corresponding to the melting-point of pure antimony. Hardened steel articles can also be tempered by giving them a preliminary heating to a temperature below about 200° C.

* See page 142.

and then immersing them in a molten lead or lead alloy bath of the appropriate tempering temperature.

To prevent the lead from adhering to the steel articles they are usually coated with soft soap, blacklead paste, or saturated salt water. An alternative coating for this purpose can be made as follows: Powdered charred leather, 1 part, fine flour $1\frac{1}{2}$ parts, and salt, 2 parts; mix with water to a pasty consistency. The coated parts must

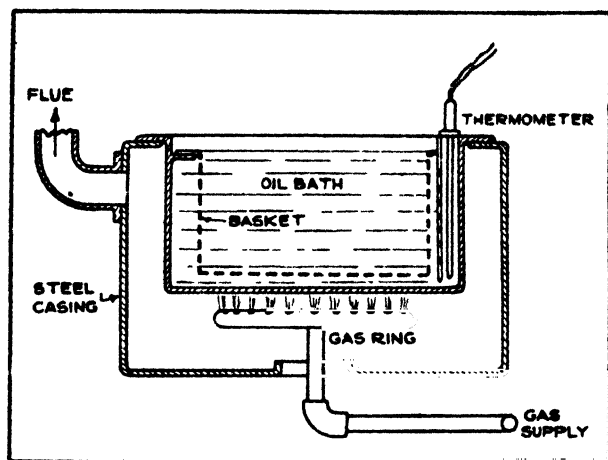


FIG. 72 AN OIL TEMPERING BATH, WITH WIRE BASKET FOR HOLDING THE STEEL PARTS

be dried thoroughly before placing them in the lead bath. The lead bath should be kept agitated, by stirring, in order to prevent the lower portions becoming hotter than the upper ones, due to convection action. The articles, after heating for a period, depending upon their shape and size—but usually varying from one to three hours—should be cleaned with a wire brush to prevent lead adherence and then quenched in fairly pure water; if any lead is left sticking on the metal, soft spots will occur at these places. Charcoal in powdered form is sprinkled over the surface of the lead to prevent the formation of scum or dross.

Quenching Oils. These oils are specially blended to give the required rates of cooling for various types of carbon tool steel, and also for certain alloy steels. Smaller carbon steel tools and articles which are liable to crack when quenched in cold water, or to become too brittle, are often hardened in oil or brine. A suitable quenching oil is a mixture of mineral and seed or animal oils having a high flash point, such that

no inflammable vapours are given off under working temperature conditions; a minimum flash point of about 177°C . (350°F .) is usually specified.

Quenching oils have an appreciably lower specific heat than water, the value varying from about 0.25 to 0.70, whereas for water it is 1.0; on this account they experience a correspondingly greater temperature rise when a heated article is quenched in them.

After constant use the lighter and more volatile oils are removed by evaporation, leaving only the heavier oils, which do not allow a sufficiently high cooling rate with the result that the steel is liable to be softer than when the original oil is used. It is therefore necessary to keep the oil in its proper condition by the occasional addition of fresh oils of lighter constitution. Specific gravity tests afford an indication of the state of the quenching oil.

For most quenching purposes the oil should be maintained at a temperature of 60°F to 90°F .

Tempering Oils. The tempering process, for certain purposes, is carried out by placing the hardened steel articles in an oil bath and heating the latter to the required temperature. Special blends of tempering oils are now available for this purpose; these will give tempering temperatures up to about 370°C . (700°F .). A typical oil contains 93 per cent mineral oil and 7 per cent saponifiable oil and has a specific gravity of about 0.9 and flash point of 290°C . (554°F .).

Quenching Salt Baths. Mixtures of certain salts such as potassium and sodium nitrates when molten give a range of quenching temperatures from 137°C (for 55 parts of the former and 45 of the latter salt) to 335°C for the former salt alone; sodium nitrate fuses at 280°C .

Salt baths are particularly useful for *quenching high-speed alloy tool steels* which, after soaking at the correct temperatures (750 to 850°C .) for their compositions, are quenched in salt baths at 300 to 600°C . and vigorously agitated. After attaining the salt bath temperature they are removed and allowed to cool in the air. Afterwards, the parts may be tempered in an oil bath at the desired temperature, e.g. 100 to 350°C .

It is also possible to use these salt mixtures for tempering purposes since they give a range corresponding to all the tempering temperatures shown in Table 35. For higher temperatures, such as those required for heating steels, mixtures of other salts, such as barium chloride, potassium chloride, and sodium chloride, are employed. Thus, a mixture of 3 parts barium chloride and 2 parts potassium chloride gives a temperature range of 750°C . to 850°C .; for lower temperatures the proportion of potassium chloride should be increased.

Notes on Hardening Steels

The following practical considerations are applicable not only to carbon tool steels but also to certain of the alloy tool steels.

(1) *Rate of Cooling.* When a steel is quenched from its appropriate temperature for hardening, the degree of hardness will depend upon the initial temperature of the cooling medium and upon the actual rate of cooling in the medium. This rate is governed by the physical

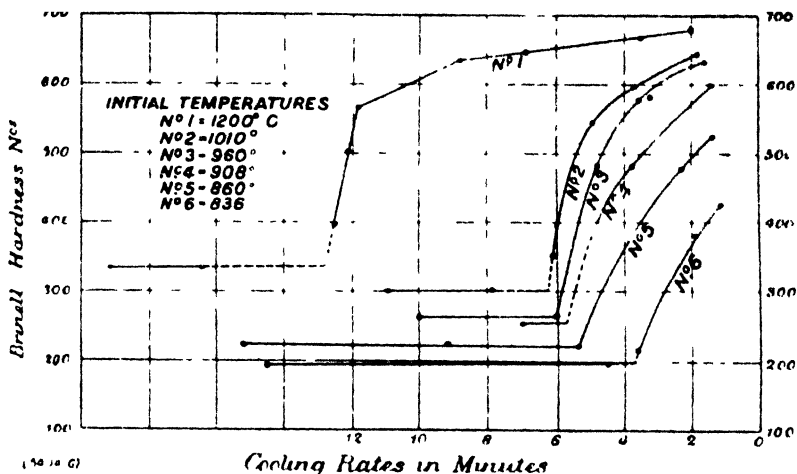


FIG. 73 EFFECT OF INITIAL TEMPERATURE AND COOLING RATE UPON THE HARDNESS OF CHROMIUM STEEL

properties of the medium, its relative mass or volume in relation to that of the steel article, the degree of agitation of the medium and the size and shape of the article, the effect of the latter influencing factors is dealt with later.

In general, as previously stated, the more rapid the cooling the harder will the steel become, within certain limits, similarly, slower rates of cooling are associated with less hard structures.

Fig. 73* illustrates the effect of different rates of cooling upon the hardness of a chromium steel containing 6.15 per cent chromium and 0.63 per cent carbon. The curve also shows the influence of another factor, namely, *the initial quenching temperature*, the higher the latter temperature is, the harder the steel resulting at any given rate of cooling.

* "The Hardening and Tempering of Steel," Professor C. A. Edwards (*Engineering*, 8th March, 1918).

In connection with the results shown in Fig. 73, the initial temperatures of cooling ranged from 1200° C. down to 836° C., and the rates of cooling from 2 to 20 minutes. The material was heated in the form of 1-in. cubes, in an electric furnace, and then cooled at various rates by placing in different parts inside or outside the furnace.

The maximum hardness was obtained when the steel cube was cooled in 2 minutes from 1200° C., and was about 685 on the Brinell scale.

When the cubes were cooled in air in the ordinary way from 1000° C. the hardness was 642, the specimen taking about half an hour to cool in still air upon an asbestos pad.

The hardness when the specimen was allowed to cool for one hour in the furnace was 281.

(2) *Quenching Medium.* It will be evident from what has already been stated that the rate of cooling is governed largely by the nature of the quenching medium and its temperature. Thus, if a piece of red-hot high-carbon steel were plunged into cold water and moved about quickly it would attain its maximum hardness and tensile strength, but would be brittle. If quenched in boiling hot water, it would be less hard and brittle. Oil and brine are used for quenching baths in cases where extreme hardness is undesirable or there is a risk of cooling stresses, distortion, or cracking when cold water is employed. In the case of small articles such as drills and reamers, where the rate of cooling would be too great if water were used, so that brittleness would occur, a high flash point mineral oil would be employed to give a slower rate of cooling. Watchmakers' drills are often hardened by heating them to a red heat and pushing them into sealing wax or pitch, in order to prevent too rapid cooling.

In instances where a rapid cooling action is necessary for obtaining extreme hardness, as for glass drills, the heated steel objects are quenched by holding them under the surface of mercury, which has a much greater heat conductivity than oil or water and a higher specific heat.

Certain of the alloy steels, for example the grade of nickel-chrome steel known as the "air-hardening" one, are hardened by heating to the recommended temperature and cooling in a blast of air; in this connection it may be mentioned that very small tools used by watchmakers are sometimes hardened by heating to a cherry-red heat and cooling by waving in the air.

(3) *Heating Steel Articles.* It is important when hardening to be able to obtain a uniform temperature in the furnace; to control this temperature; and to have proper means for ascertaining the correct temperature at the place where the parts are being heated.

The principle employed in heating up objects for hardening is to heat them sufficiently slowly to allow the temperature to become uniform throughout the whole mass of the objects: otherwise, if heated too quickly the surface corners and projecting parts, such as the teeth of wheels or cutters, become overheated, and when subsequently quenched they become brittle and useless.

Another effect of too rapid heating is to cause the objects to warp, or deform, owing to the varying temperatures at different parts of the objects causing unequal expansion stresses.

It is also very important to avoid overheating steels of all kinds, as this causes oxidizing or "burning," often with the formation of slag or impurities, the strength properties are reduced, and cracks or even fractures occur during the quenching operation.

The fracture of a burnt or overheated steel is white and crystalline, more particularly at the surface or edges. If the steel is not at a uniform temperature before quenching, it is apt to crack during quenching owing to unequal contraction.

Small objects can be effectively heated in a muffle or smith's furnace by enclosing in a wrought-iron pipe, closed at one end, the pipe being repeatedly turned during the heating process to ensure a uniform temperature.

(4) *Effect of Mass.* The "mass," that is to say, the bulk or size of the object to be hardened, has an important influence on the final hardness. Large solid objects when quenched cool from the outside inwards at a given rate, whereas in the case of small objects of the same material the heat is conducted away much more quickly, and the effect of a higher cooling rate is obtained. It is therefore more difficult to harden large masses satisfactorily, and in many cases the microstructure and mechanical properties vary considerably from the outside to the centre.

The effects are most marked for large masses when the quenching is most drastic. In this connection the results may be quoted of tests* upon exactly similar steel cubes, each of 18 in. side, heated gradually to the same uniform temperature of 900° C. throughout their whole mass, and then allowed to cool in the following ways: (a) upon knife-edges in air, (b) by plunging in oil, and (c) by plunging in cold water. The air-cooled cube was found to give uniform strength results throughout its whole mass.

The oil-cooled cube, which cooled fairly rapidly, gave a higher tensile strength and lower elongation than in the case of the air-cooled one, and these properties were fairly uniform throughout the mass.

* "The Effect of Mass," E. F. Law (*Proc. Iron and Steel Institute*, 1918).

The water-quenched cube cooled much more rapidly than the others, and the tensile strength and elongation were found to vary considerably from the centre to the outside. It was noticed that there was an important difference between the cooling in oil and that in water, there being a sudden slowing up in the "cooling in oil" case in the lower ranges of temperatures as compared with the cooling in water. The time required for the centre of the cube to cool from $900^{\circ}\text{C}.$ to $540^{\circ}\text{C}.$ was almost the same in both cases, but in the cooling from $540^{\circ}\text{C}.$ to $315^{\circ}\text{C}.$ the cube in oil took nearly *twice the time*, and from $315^{\circ}\text{C}.$ nearly *four times* as long. The differences were even greater for the outside of the cube.

It should be remembered that with large or complicated shapes in which different parts cool at different rates, internal stresses are very apt to occur during cooling: in general, large and intricate parts should not be quenched in cold water, but in hot water, brine, oil, or air. Fragile and large objects are frequently hardened by quenching in tallow, brine, or lime, or in warm water first, and finished in oil.

Tools, dies, and parts of complicated shape may be partially quenched in water until they have fallen in temperature to a black heat, and then plunged into hot water or oil, in this manner hardening stresses are avoided and the risk of distortion minimized.

A method adopted for hardening milling cutters and irregularly shaped articles, which are liable to crack or to warp, is to quench in warm water at $30^{\circ}\text{C}.$ to $38^{\circ}\text{C}.$, or in a bath of water with an oil layer on top

(5) *Effect of Shape of Article.* Long slender objects, such as tubes or rods, should be quenched in a vertical position in a warm bath.

Parts having hollow shapes, such as partially drilled objects, hollow cylindrical shapes with one end closed, hollow milling cutters, dies, and similar objects should always be quenched with the open side uppermost, in order to allow the steam to escape, otherwise it would prevent the hardening medium from coming into contact with the hollow portions of the object and cause softness there, this is the principle of a local softening process for hardened parts. In the case of objects of varying thicknesses, the thickest parts should enter the quenching medium first.

When parts are quenched they should be held, or rather moved about, in the liquid until such time as they are quite cool; they must not be thrown in and allowed to fall to the bottom, otherwise the lower surface parts near the bottom will not cool as quickly as the other portions, and unequal cooling stresses and warping may occur.

Steel objects having holes in them are apt to crack during hardening

unless carefully attended to; it is often advisable to plug holes which do not require to be hardened with soft iron rod or fireclay.

Obtaining Bright Results. Normally, polished carbon steel articles become dull when hardened by heating and quenching. If, however, the quenching solution consists of 3 to 5 per cent of strong sulphuric acid in water, the parts will retain their polish after quenching. This method can be used for punches, drills, taps and reamers. After quenching, thorough washing in clean water is necessary.

Volume Change in Hardening

In general the volume is increased by hardening and reduced by subsequent tempering. Thus, on hardening steel bars 4 in. long by $\frac{7}{8}$ in. diameter the length was found* to increase by 0.0001 in. to 0.0014 in., and the diameter by 0.0003 in. to 0.0036 in.

On tempering, the length decreased 0.0017 in. to 0.0108 in. as compared with the original 4 in., and the diameter was increased 0.0003 to 0.0029.

In the case of high-speed tungsten-chromium steel the following values were obtained† -

Tempering temperature ° C.	0	100	200	300	400	500	600	700	800
Brinell hardness.	700	680	670	655	650	640	570	500	400
Specific gravity.	8.67	8.685	8.680	8.688	8.680	8.600	8.620	8.640	8.660

Automatic Electric Hardening Furnace

An interesting method of hardening steels which gives uniform results in production hardening is embodied in the Wild-Barfield hardening apparatus, which is shown illustrated in Fig. 74.

The principle of the method used depends upon the fact that at the critical or *A_c 2* point (which is the proper temperature for hardening) the metal becomes non-magnetic. A galvanometer is provided for notifying the operator immediately the correct quenching temperature has been attained.

The furnace has a refractory heating chamber surrounded by a closely wound helix of alloy wire, the electrical resistance of which is used to produce the necessary heat. A controlling resistance in the circuit of this coil permits of varying the strength of the current and thereby the heat of the furnace. Superimposed on the main heating winding is the secondary or indicator winding electrically connected

* J. E. Storey, *Amer. Mach.*, 20th February, 1908.

† Professor C. A. Edwards.

to the *magnetic indicator* on the control panel. The whole furnace unit, as above is thoroughly lagged to reduce heat losses to a minimum, and is surrounded by a substantial case of polished aluminium with cast ends

The *control panel* carries—

(a) The magnetic indicator by which a visual indication of the quenching moment is given to the operator

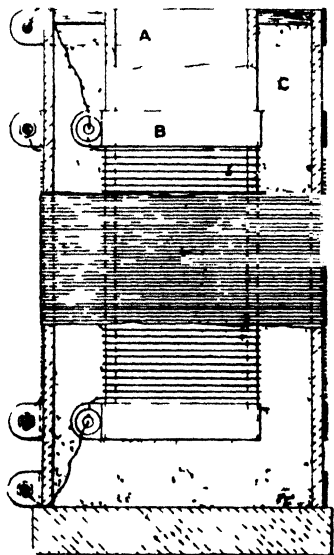


FIG 74 THE WILD-BARFIELD AUTOMATIC HARDENING FURNACE

(b) The regulating rheostat for controlling the furnace temperature.

(c) The warning lamp which lights up when the excess temperature cut-out operates

(d) A pyrometer for regulating the superheat of the furnace and for use when refining or annealing

The electrical circuits of the complete equipment are shown diagrammatically in Fig 75. *D* is the secondary or indicator winding on the furnace casing, *F* is the primary or heating winding on the furnace chamber, *MC* is the moving coil of the magnetic indicator. This has a pointer attached to it which moves over a scale like an ammeter or a voltmeter, *S* and *P* are the secondary and primary windings of a coil generally designated the compensator, *W* is the

winding on an electromagnet between the poles of which the coil MC moves.

Normally, an electromotive force is induced in D , which is opposed and completely neutralized by an equal electromotive force induced in S .

As soon, however, as a piece of steel is introduced into the furnace, the electromotive force in D is augmented by the presence of the steel,

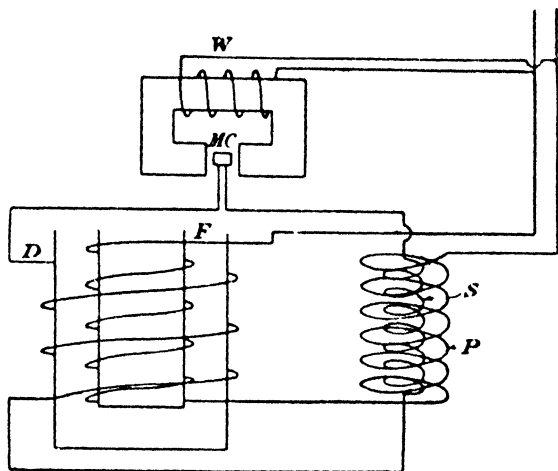


FIG. 75. DIAGRAM OF
ELECTRIC CIRCUIT AUTOMATIC ELECTRIC FURNACE

the electromotive force opposing it in S is overpowered and a small current circulated through MC , causing it to move on its axis, the pointer generally being deflected right across the scale against a stop, against which it vibrates so long as the steel is in the magnetic condition.

When the steel has nearly attained the non-magnetic condition the pointer leaves the stop and comes slowly down the scale. Finally, when the steel has lost its last trace of magnetism and is in exactly the right condition for quenching, the pointer ceases to move.

In practice the operator simply charges the furnaces with the steel to be hardened, and allows heating to continue until the pointer of the magnetic indicator shows when to quench.

Referring to Fig. 74, the inner pot A is the furnace chamber, and contains a special mixture of salts having a comparatively low melting,

but a high vaporizing point. The pot *A* is wound with a heating coil *B*, and between this coil and the outside of the furnace *D* is a special non-conducting lagging *C*. The ends of the outside insulated copper windings *E* are connected to a special galvanometer.

When a current of electricity is passed through *B* it quickly heats the furnace and renders the salt molten. The winding *B* also magnetizes any steel article that is placed in the furnace. Immediately the critical temperature is attained the steel loses its magnetism and the galvanometer indicator at once notifies the fact; the articles are then at the correct temperature for quenching.

Case-hardening Carbon Steels

These are low-carbon steels of the mild steel class containing from 0.10 to 0.20 per cent carbon, with 0.25 to 0.4 per cent silicon and 0.55 to 0.65 per cent manganese. In the normalized condition these steels have a yield point of 14 to 15 tons per sq. in. and a tensile strength of 25 to 35 tons per sq. in., with 25 to 30 per cent elongation on $1\frac{1}{2}$ in. bar and 50 to 60 per cent reduction of area. The Brinell hardness in the normalized condition is about 110 to 140.

Such steels respond to heat-treatment to a certain degree. Thus, when a 0.12 carbon steel is water quenched from 900° C. and then reheated to 760° C. and water quenched it gives a yield point of 20 to 24 tons per sq. in. and tensile strength of 35 to 40 tons per sq. in., with 20 to 25 per cent elongation and 50 per cent reduction of area, with an Izod impact test value of 50 ft.-lb.

Although not so strong or tough as the alloy case-hardening steels mentioned later in this volume, the carbon steels in question are capable of giving a sufficiently tough core combined with an extremely hard surface layer, after carburizing, for a wide range of engineering applications.

Typical examples of the latter include case-hardened pins, fork-ends, small gear wheels, camshafts, levers, spindles, stampings, pressings, valve tappets, valve rocker rollers, ratchets, pawls, small mechanisms, parts requiring hardened wearing surfaces, e.g. holes in levers and fork-ends, etc. In general such steels are employed chiefly for lightly stressed parts requiring hard wearing surfaces.

The Case-hardening Process

The low-carbon (and also alloy case-hardening) steels are given an extremely hard surface layer by a suitable carburizing method, whereby the percentage of carbon is increased to about 0.90 to 1.10 per cent; by suitable heat-treatment, e.g. heating to about 850° C. to 900° C.

and water quenching, the full hardness of the skin is attained, leaving the core in about its ordinary condition.

This process enables parts to be machined before hardening, gives greatly improved wearing qualities combined with a tough but ductile core, and avoids the brittleness associated with the higher carbon steels when hardened throughout their mass.

The original process of case-hardening, which is still employed in certain instances, consists in packing the machined steel parts in iron boxes and lining the base, sides, and top with carbonaceous material such as charcoal bone black, leather, horn parings, etc. The spaces between the articles are also packed with the same material and the box is sealed so as to be air-tight. It is then placed in a furnace and heated to about 870° C. to 950° C. for a period varying from 4 to 15 hours according to the depth of case or skin required.

The articles are either quenched from 900° C. upon withdrawal from the boxes or are allowed to cool in the box and then reheated to about 900° C. and quenched. They are then reheated to just above the A₁ critical point, i.e. at about 760° C., and quenched; this process *refines the structure*. Internal stresses are largely removed by a subsequent reheating to about 200° C.

The cementation temperature at which the ferric carbide passes into solution in the iron depends upon the carbon content, being higher for the lower carbon contents. Thus, for carbon percentages of 0.15, 0.30, 0.50, 0.70, and 0.90 the corresponding temperatures are 885°, 830°, 780°, 750°, and 740° C. respectively.

As the percentage of carbon increases from 0.90 the formation of free cementite occurs, and the temperature again rises.

In the case of a low-carbon content steel, at about 900° C. the solution of carbide of iron in iron is a dilute one, capable of taking up or of dissolving much more carbon or carbide of iron than it originally contained. If, then, this steel is placed in contact with a suitable carburizing agent, whether solid, liquid, or gaseous, carbide of iron is formed therefrom, and is dissolved and diffused into the steel.

The carbon content of the "case" can be controlled to a large extent by regulating the cementation temperature and the composition of the carburizing medium, whilst the depth of the case is governed by the period of time during which the cementation temperature is maintained.

If the steel is allowed gradually to cool down, it will be found to consist of an outer shell of pearlite or pearlite and cementite, with an inner core of ferrite and pearlite, the former being in excess. The ferritic structure of the core is left rather coarse by the carburizing

operation, so that it is advisable to reheat the articles as previously described.

The operation of hardening the carburized steel part leaves the steel with a ferritic or ferritic-and-pearlitic core, or interior, with an outer case, or shell, of pearlite and cementite.

The structure of a case-hardened mild steel can be examined microscopically, and it can at once be seen whether the case is rich or poor in carbon, and to what depth it has penetrated. Fig. 76 shows a typical microphotograph of case-hardened mild steel.

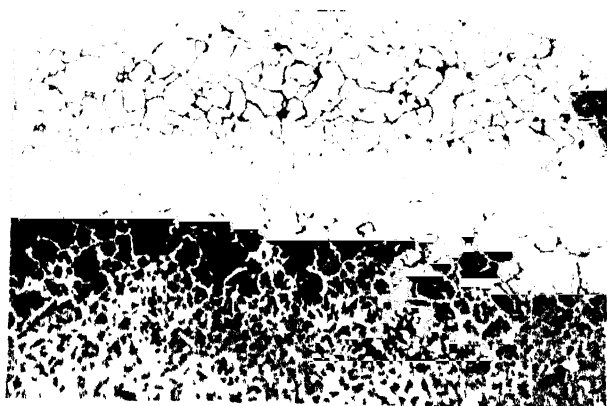


FIG. 76. MICROPHOTOGRAPH OF CASE-HARDENED MILD STEEL. 25

A convenient method* for examining this steel is to polish in the usual manner, after heating in charcoal powder to about 760 °C. (just above the recalescence point) and allowing to cool slowly; this process will not carburize the metal but will convert the carbon of the hardened steel into the pearlitic condition. By etching, after polishing, with a strong acid, the depth of the carburized layer and the approximate carbon content may be readily ascertained. Alternatively, the specimen may be ground at right angles to the surface, polished, and acid-etched, when the high-carbon, or hardened layers, will appear as dark portions gradually merging into the lighter parts of low-carbon steel, as shown in Fig. 76.

Heat-treatment Processes

The temperature of quenching case-hardening steel is important, from the point of view of the mechanical strength properties of the

* Osmond.

core. If too high the core will be harder and tougher but the case will be brittle. If too low there is a risk of 'soft spots' due to the breaking down of the solid solution state. Similarly, if the cementation temperature is too high the case will contain a higher carbon content and will be more brittle, although harder. It may here be of interest to quote the results of some tests* made upon 1 in. bars of 0.17 per cent carbon steel (with 0.08 per cent silicon and 0.85 per cent manganese). The bars were carburized for $2\frac{1}{2}$ hours in a box and some were cooled in the box reheated to 900 °C and quenched in water. The case was

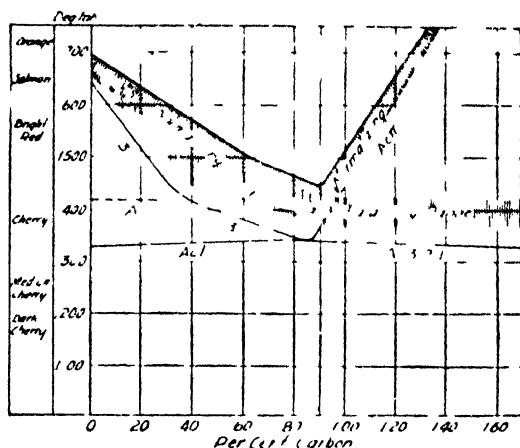


FIG. 77. SHOWING THE NORMALIZING, ANNEALING AND HARDENING RANGES, TEMPERING RANGES AND COLOURS OF CARBON STEELS.

then ground away and the core tested. The bars gave a mean yield point of 37 tons per sq. in., tensile strength of 52 tons per sq. in. with 22.6 per cent elongation and a Brinell hardness of 302.

Other bars were cooled in the box and reheated to 900 °C and quenched. They were then reheated to 770 °C and quenched, after which the case was ground away. The yield point and tensile strength were 29.8 and 41.7 tons per sq. in. respectively, with 35 per cent elongation and a Brinell hardness of 201. In the former condition the ferric carbide in the case and core can dissolve at the existing temperature provided a large excess of carbide is not present but the case becomes overheated and is therefore crystalline, as shown by the

* Commercial Steels and their Heat treatment, J. B. Hoblyn, *Proc. Inst. Autom. Engrs.*, 1918.

mechanical test figures. In the latter process the structure is refined and the material is in the best condition for practical purposes.

Subsequent reheating to about 150° C. to 250° C. in an oil bath for the purposes of relieving quenching stresses is recommended in most cases. In cases where *parts are not to be subjected to shocks* they may be quenched from 900° C. immediately upon withdrawal from the carburizing boxes and then reheated to 760° C. to 780° C. and quenched again. Alternatively, the parts may be allowed to cool in their boxes and then reheated to 760° C. to 780° C. and quenched.

Parts liable to shock effects under working conditions should be allowed to cool in the boxes, then taken out and reheated to a full cherry red (810° C. or 1490° F.) and quenched. They should afterwards be reheated to 760° C. to 780° C. (1400° F. to 1436° F.) and quenched again.

For *articles that are liable to warp*, the following treatment is recommended—

Allow the parts to cool in the boxes, reheat to a bright red (900° C. or 1652° F.), and cool in air; then reheat to 760° C. to 780° C. (1400° F. to 1436° F.) and quench. Oil quenching is often substituted for water quenching, but the case obtained is not so hard, although the risk of distortion is lessened.

Depth of Case. The depth of penetration of the carburizing carbon for any given steel depends principally upon the *time* of the carburizing process and the *temperature*. To illustrate the influence of these factors mention may here be made of some tests made by Guillet* upon iron and also steel containing 0.5 per cent carbon. It was found that the depth of case for a carburizing period of 8 hours and temperature of 1000° C. was the same in each case

When the iron was carburized at 1000° C. for periods of $\frac{1}{2}$, 1, 2, 4, 6, and 8 hours the corresponding depths of penetration of the carbon were 0.5, 0.8, 1.0, 1.3, 2.0, and 3.0 mm., thus showing that the penetration was a function of the carburizing period. When the temperature of carburization was increased from 800° C. to 1050° C. it was found that the depth of penetration after 8 hours increased progressively from 0.5 mm. to 5.2 mm.

Case-hardening Materials. Apart from the carbonaceous materials previously mentioned, there is a fairly wide range of other materials—solid, liquid, and gaseous—that can be employed for case-hardening purposes. A popular workshop method is to sprinkle powdered potassium ferrocyanide upon the heated iron or mild steel when at a cherry red heat (about 800° C. to 850° C.). The salt then fuses and traverses

* *Memoires de la Societe des Ingenieurs Civils de France*, 1904.

the surface, giving off fumes. After repeating this process several times the metal is quenched in water. The case thus obtained is very hard but of relatively small depth.

Other alternative materials that can be employed in this manner are a potassium ferrocyanide and potassium bichromate mixture in equal parts; and sodium ferrocyanide (9 parts) to anhydrous sodium carbonate (1 part). Another effective mixture, known as Guillet's, consists of barium carbonate (40 per cent) and charcoal (60 per cent); this is used in the box carburizing method.

The most effective of the carbonaceous materials appears to be a mixture of wood charcoal (9 parts) and bone black (1 part). Of a wide range of alternative materials tested by H. L. Henthcote, this gave the greatest ratio of total case volume to volume of mixture.

To obtain colour effects when case-hardening it is usual to employ a mixture of charred bone and leather, 12 parts; wood charcoal, 6 parts; potassium ferrocyanide, 1 part. The parts, e.g. tools, are first polished and degreased. They are then packed into metal containers with the case-hardening mixture mentioned previously and heated to rather lower than the usual carbonizing temperature, e.g. a dark cherry-red, for the best results. The heating period is 4 to 5 hours. After quenching in well-agitated water the parts are placed in boiling water and then removed for drying in sawdust.

The Cyanide Process

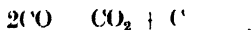
Carburizing is also effected by using *molten cyanide salts* or mixtures, whereby both the carbon and nitrogen become the active carburizing agents.

Sodium cyanide. This salt is much used commercially for case-hardening purposes and is supplied in the form of pellets or "Cyanoids" of practically pure sodium cyanide*. This salt is not used alone, however, since it would decompose too rapidly and tend to give too great a concentration of carbon in the outer layers of the case. It is therefore used with about an equal quantity of sodium carbonate in order to slow down the rate of decomposition. The use of the latter salt enables the strength of the bath to be maintained by the addition of sodium cyanide alone.

The main reaction in the cyanide bath is believed to be as follows—



and afterwards, inside the steel lattices—



* Cassel Cyanide Co. Ltd., Oldbury, Birmingham.

In all case-hardening carburizing processes the chief active reagent is generally supposed to be carbon monoxide.

When the cyanide and carbonate salts are fused and ready for use the surface is covered with a layer of graphite in order to prevent excessive decomposition. the layer should not be too thick as some air must be permitted to pass to the cyanide for the proper reactions to occur. The hardness of the surface layer of steel treated by the cyanide method is due not only to increased carbon content but also to increased nitrogen content; the presence of nitrogen prevents the carbon concentration in the case rising sufficiently to promote formation of the brittle cementite which occasionally occurs and is the cause of subsequent "exfoliation" or cracking of the case during quenching

The usual procedure for cyanide hardening is to leave the steel articles in the bath for about 2 hours, then quench in water or oil or cool in air, carburizing should take place at 930° C. to 950° C. (for delicate parts, 850° C.) The parts after the first quenching should be reheated to 760° C. and quenched in water

If, however, carburizing takes more than 2 hours, after the first quenching the parts should be reheated to 900° C. and quenched in water or oil

If maximum hardness is not required or if the *parts are liable to distort*, the quenches should be done in oil

For cheap classes of work with a thin case of, say, 0.005 in., it is usually sufficient to quench direct from the cyanide bath.

In regard to the depth of the case, this depends upon the temperature of the cyanide bath and also upon the period of immersion. Fig. 78 illustrates the effects of these factors upon the depth of case for a normal case-hardening steel of 0.10 to 0.20 per cent carbon

It should be noted that the carbon content of the case is usually about 0.8 per cent with the cyanide and carbonate bath, but a content of 1.1 per cent can be obtained in a cyanide bath if kept to its maximum strength. In regard to the carburizing times, it will be seen from Fig. 78 that depths of case up to 0.06 in. can be obtained under favourable conditions. In practice it is usual to reckon that a case of 0.005 in. is obtained in 30 min. carburizing time, 0.015 in. in 1 hour; and 0.030 in. in 2½ hours. The cyanide process is usually considered to be the cheapest and quickest for cases up to 0.015 in. depth; it is possible, however, by the addition of special ingredients to obtain depths of case up to 0.100 in.

For steel parts requiring deeper cases than those obtainable by the use of ordinary cyanide baths, special case-hardening salts,

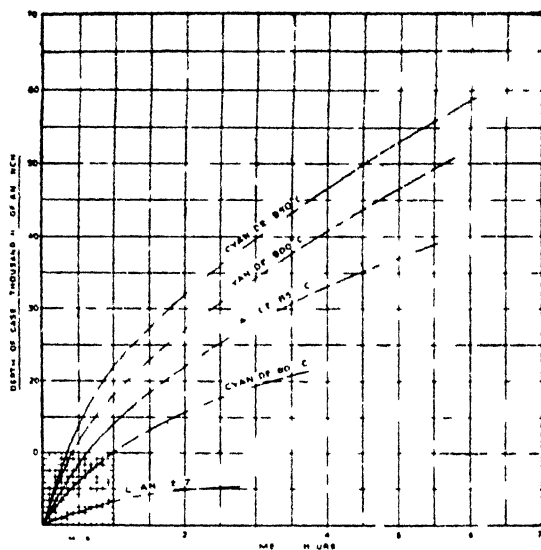


FIG. 78 EFFECT OF CYANIDE BATH TEMPERATURE AND TIME OF IMMERSION UPON DEPTH OF CASE

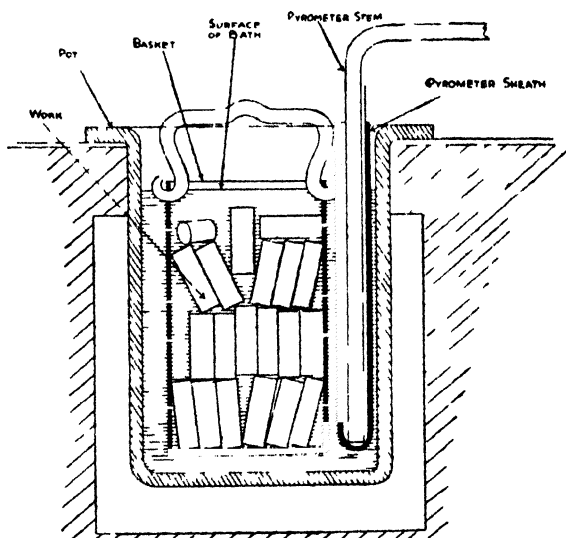


FIG. 79 STEEL PARTS IN CYANIDE POT. THE PARTS CAN BE PACKED IN ANY CONVENIENT MANNER AS THE MOLTEN SALT FILLS ALL INTERSTICES

such as Cassel's "Rapideep" and Edgar Vaughan's "Perlton," are recommended.

Among the advantages claimed for the cyanide process over pack case-hardening are: (1) The reduced warping and distortion due to more even and quicker heating; (2) absence of scaling, the treated parts being clean and of pleasing appearance; (3) cheapness; (4) rapidity; (5) absence of decarburization; and (6) tougher core resulting from the shorter period of exposure to the high temperature required in carburizing; this enables the core to be more readily refined than for pack-hardened parts.

The ease with which the cyanide process can be carried out renders it applicable for the surface-hardening of inexpensive articles which otherwise would not pay for hardening, their useful life is extended considerably. Small parts which are difficult to harden by the pack-hardening method can be case-hardened by placing in a wire basket and immersing in the molten cyanide. Moulds for plastic materials can be made from relatively soft steel and then given a high degree of surface hardness of clean finish by the cyanide process. In general, the surface finish after case-hardening by the cyanide method is a clean and bright one so that any subsequent polishing necessary requires a minimum of time.

Carburizing in Gases

Articles can be case-hardened by heating them in hydrocarbon gases to the proper temperature. Typical examples of gases which have been used are acetylene, coal gas which has been freed from sulphur by bubbling through carbon disulphide, and petroleum vapour. The results of tests upon $\frac{1}{4}$ -in. rods heated for about an hour at 880°C . in pure acetylene gas showed that the acetylene was completely decomposed, the carbon being deposited upon the specimen; the thickness of the case was 0.0064 in. after three-quarters of an hour. With a mixture of 1 volume acetylene and 12 volumes coal gas the specimen, after an hour's exposure at 880°C ., was found to be coated with carbon and to have a case of 0.0147 in. thick.

Mention should here be made of the case-hardening method, known as *nitriding*, whereby alloy steels and cast irons of special composition are surface-hardened by heating to about 500°C . in contact with ammonia, this method is described in Chapter VII.

The Shorter Hardening Process

This method utilizes a high-temperature flame, such as the oxy-acetylene blowpipe, to heat the surface metal above the critical

temperature until it changes to the γ -iron condition and the carbon is dissolved in the iron: this is followed by a rapid cooling so that there is no time for the iron to change to the α -iron state and for the carbon to come out of solution. Thus, the steel is converted from the relatively soft pearlitic to the very hard martensitic condition.

It will be seen that, unlike the pack-hardening or cyanide case-hardening methods in which the carbon content of the surface layer is increased, the Shorter process does not alter the carbon content of the surface steel, the composition of this being the same as for the core.

The hardness resulting from this process depends upon the composition of the steel. The following table illustrates this point—

TABLE 36
HARDNESS AND CARBON CONTENT (SHORTER PROCESS)

Percentage of Carbon	Original Brinell Hardness before Treatment	Brinell Hardness after Shorter Treatment
0.15	140	200
0.30	160	350
0.45	200	550-600
0.55	250	600-650

It should be mentioned that alloy steels of about 0.35 per cent carbon content containing nickel, chromium, molybdenum, etc., give good surface-hardening results with the Shorter process, and have the additional advantages of tougher and stronger cores.

Special flame hardening machines are now in use to cover a wide range of sizes and shapes of parts. In particular, gear teeth, crankshafts, camshafts, and plain journals are provided for in existing Shorterizing machines. Thus, special means are provided for hardening the flanks of gear teeth by raising the temperature of the surface metal progressively to above the critical point, i.e. between 750° C. and 850° C., according to the composition and quenching. In this way the hardness is raised to 600–650 Brinell from the original 200–250 value.

It is true that *certain volumetric changes* occur when steels are heated above the critical temperature and rapidly cooled, but as the treatment in the present method is purely local, a comparatively small amount of metal is concerned; further, the mass is kept cool as the treatment progresses over the surface to be hardened. For this reason gear teeth can be hardened with so little dimensional change that it can be neglected in most cases. In extreme instances a slight amount of grinding can be allowed for in the machined gear. Gears of all sizes

are amenable to treatment by this process; thus, the machines available can deal with gears ranging from those of a few pounds up to 4 or 5 tons. Worms and worm wheels can be hardened on their working faces; thus, the oxy-fuel gas flame travels in a horizontal direction to the rotating (horizontal axis) worm thread and, after quenching by means of five sprays, causes an intensely hard surface to be formed on the contact area of the worm.



FIG. 80. TREATMENT OF A LARGE PINION WHEEL BY THE SHORTER PROCESS.

An improved process employed for crankshafts, pins, journals, tools, etc., is that known as the Shorter Double-Duro one. It gives a very hard zone with a gradual transition to the inner core metal; the process controls the depths of the hardened zone between relatively wide limits and avoids soft spots and exfoliation. Fig. 83* shows the manner in which the hardness of the case and core of a $4\frac{1}{2}$ -in. diameter crankpin varies from the surface inwards. The steel in question contained 0.35 per cent carbon and 1.2 per cent manganese. It will be seen that there is a progressive reduction of hardness until at a depth of 0.02 in. the original core condition is reached.

* "Hardening Crankshafts. The Shorter Double-Duro Process for Cylindrical Surfaces." *Aut. Engr.*, August, 1936.

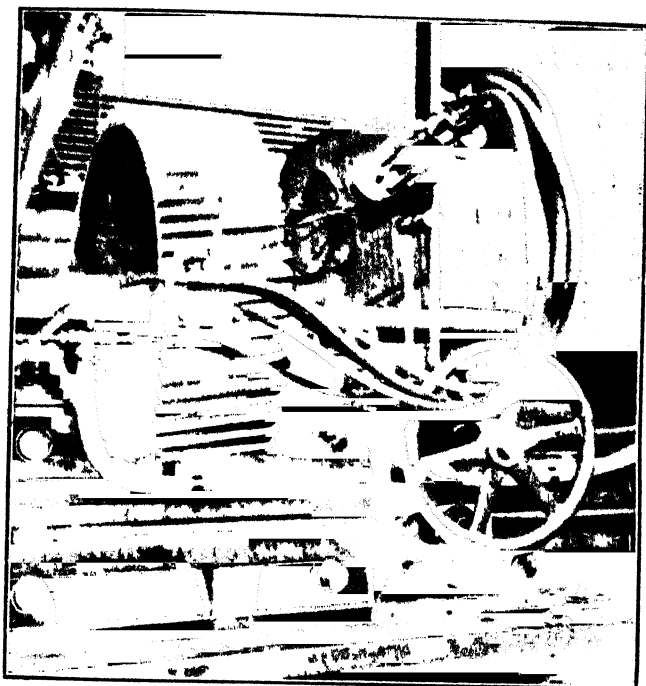


FIG. 81. THE SHEFFIELD STEEL GEAR HARDENING MACHINE.

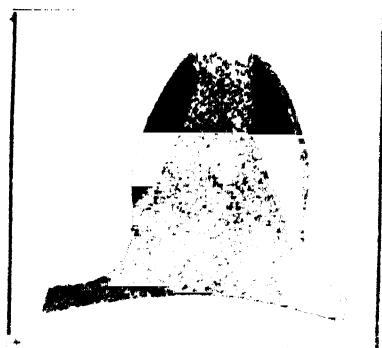


FIG. 82. ETCHED SECTION OF SHORTER-HARDENED GEAR TOOTH. THE DARKER LINES CORRESPOND TO THE HARD PARTS OF TOOTH.

Induction Surface-hardening Process

A method much used in America, and to some extent also in this country, is the electric induction one based upon inductive heating in which a high-frequency current is first transformed from high to low voltage, and the heavy low-voltage current is passed through inductor blocks which surround the bearing journal to be hardened (Fig. 85) without actually touching it. The inductor block current

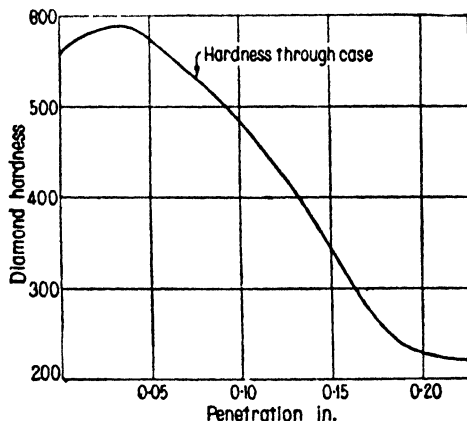


FIG. 83 THE GRADATION OF HARDNESS BETWEEN THE CASE AND CORE ON A $1\frac{1}{2}$ IN. DIAMETER CRANKPIN (SHORTER PROCESS)

induces current in the surface of the metal which the block surrounds, and it is this induced current which heats the surface to be hardened. When the area in question has been thus subjected to an accurately controlled high-frequency current for the proper length of time, the electrical circuit is opened and simultaneously the heated surface is quenched by a spray from a water jacket built into the inductor block.

In the case of a crankshaft, when all of the main and crankpin bearings have been hardened the entire shaft is reheated to a low temperature, i.e. below about 200°C ., in order to remove any internal stress effects. A final grinding operation is then necessary to give the finished precision dimensions. The process, it will be observed, is similar in principle to the Shorter one and gives a surface-hardened zone blending gradually into the core.

The inductor blocks (Fig. 84) are hollow and contain holes for the quenching spray. Accurate time and temperature controls permit the production of the correct temperature in a minimum period of time.

In regard to the heating currents, specifically chosen frequencies from 2000 to 10,000 cycles are being used extensively at the present time. Currents of this nature, when caused to flow through an inductor, will produce a high-frequency magnetic field within the region of the inductor. When a magnetic material such as steel is placed within this field, there is a dissipation of energy in the steel both due to hysteresis and eddy currents. Owing to the well-known skin effect, the heating is limited to the outside layers.

When the temperature of an inductively heated steel bar arrives at the critical value, all heating due to hysteresis ceases and that due to eddy currents continues at a greatly reduced rate. Since the entire action goes on in the surface layers, only that portion is affected. The original core properties are maintained and the surface hardening is

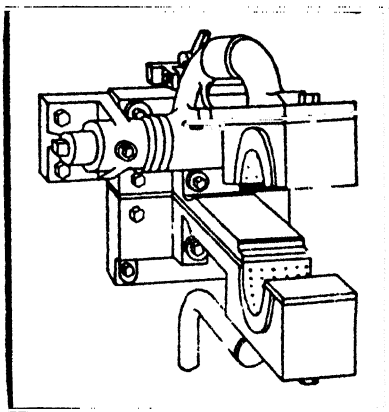


FIG. 84. THE TOCCO ELECTRIC INDUCTION HARDENING UNIT FOR CYLINDRICAL PARTS. THE UPPER ARM IS HINGED

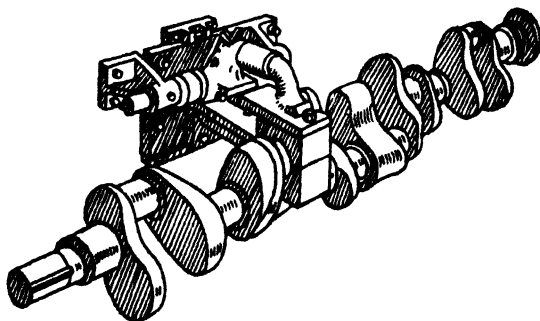


FIG. 85. SHOWING THE TOCCO HARDENING UNIT APPLIED TO CRANKSHAFT JOURNAL

accomplished by quenching when complete carbide solution has been attained in the surface areas. Continued application of power causes an increase in depth of hardening, for as each layer of steel is brought

to temperature the current density shifts to the layer beneath, which offers a lower resistance. It will at once be obvious that the selection of the proper frequency and control of power and heating time will make possible the fulfilment of any desired specifications of surface hardening.

Induction hardening produces a hardness which is maintained through 80 per cent of its depth, and from there on toward the core a gradual decrease through a transition zone to the original hardness of the steel as found in the core which has not been affected. The bond is thus ideal, eliminating any chance of spalling or checking.

The surfaces of cylinder liners for petrol and Diesel engines can be inductively hardened.

In addition to the selective surface hardening of steels, there have been other applications of induction heating of rather a unique nature. Hardening a piece of steel and brazing to copper and other metals may be done simultaneously. A small section of a previously hardened object can be drawn or softened to a condition possessing ready machinability. Heating for forging and upsetting has been found to be a particularly satisfactory use for induction heating.

It is recommended that the steel used for parts to be hardened by this process should be of the fine-grained type. After forging the shaft or part should be normalized for machining.

Change of Volume after Case-hardening

The case-hardening treatment is attended with certain physical changes, one of which is a small increase in the volume after case-hardening—that is to say, a diminution in the specific gravity. Parts required for accurate work, such as fine limit work, plugs, gauges, etc., must be ground after hardening, and allowances must be made for this specific gravity effect.

Local Hardening of Steel Parts

In many cases, certain parts only of an article, such as those subjected to wear, abrasion, or blows, require to be hard, with the rest of the material soft. There are several methods available for realizing this result, including the Shorter and electric induction ones.

The Vickers process for hardening the wearing parts only of gear wheel teeth and similar objects, so that there is no risk of warping or inaccuracy such as often occurs with mass hardening, consists in drawing the exceedingly hot flame of a suitably constructed oxy-acetylene blowpipe across the tooth face or other surface. The temperature of the flame is so high that the surface of the steel, to a depth of

from $\frac{1}{8}$ in. to $\frac{1}{2}$ in. as desired, is at once raised to the hardening temperature. As the flame passes along there is an equally rapid fall of temperature due to the absorption of heat from the hot part by the cool remainder of the tooth, with the result that a dead hard skin is formed with no distortion effects as in the similar Shorter process.

Carbon steels may be locally hardened by covering parts to be left soft with a thin metal shield in iron or steel of about 28 S.W.G., so that upon quenching steam is formed between the shield and the metal, which prevents the cooling medium from reaching the metal beneath the shield. Alternatively, a pad of fireclay or asbestos, held on with iron wire, may be used.

Obtaining Soft Areas

In case-hardening processes, areas which require to be left soft for machining, etc., should be covered with iron or steel plates or asbestos pads, or the "areas of softness" may be plated with copper or nickel before case-hardening; it has been found that the carburizing material will not penetrate such plated areas.

Another method is to leave portions of the articles required to remain soft rather fuller, by $\frac{1}{16}$ in. to $\frac{1}{8}$ in., than the finished size, and to grind off these parts after carburizing. This removes the high-carbon material, and the article then may be reheated and quenched in the usual manner.

Copper plating is often employed to protect parts that are to retain their original softness when case-hardening the rest. Used in conjunction with the cyanide-hardening method, this protective means gives satisfactory results. It is necessary that the plating shall be rather thicker than for pack hardening, because a liquid carburizing agent makes much closer contact with the metal than does a solid cement.

The steel should be cleaned thoroughly before plating by pickling or similar means. If oxide in any form is present the parts should be immersed in a pickling bath, consisting of 1 part hydrochloric acid to 4 of water, they should afterwards be rinsed in cold water and dried by dipping into boiling water.

To prevent copper deposition on the areas to be carburized, these are coated with special preparations known as "stop-off" materials. Sometimes the whole surface is copper plated; afterwards the parts to be carburized have the copper plating removed by means of a buff.

Necol cellulose enamel has been found to give satisfactory results for "stopping-off," or protecting areas which have to be left soft, after the cyanide case-hardening operation.

Fig. 86 shows a micro-section of a copper-plated specimen after a treatment in cyanide* at 850° C. for 2 hours 40 minutes. The section is cut at right angles to the surface which was in contact with the cyanide; it will be observed that there is no trace of carburization, but slight diffusion of the copper into the steel.

Parts which have been case-hardened by pack-hardening methods are usually covered with deposits. The latter can be removed by immersion in a 1 : 10 caustic soda and water bath or, for harder deposits, by dipping into a solution consisting of 1 part of sulphuric acid to 2 or 3 parts of water, followed by immersion in the caustic soda solution.

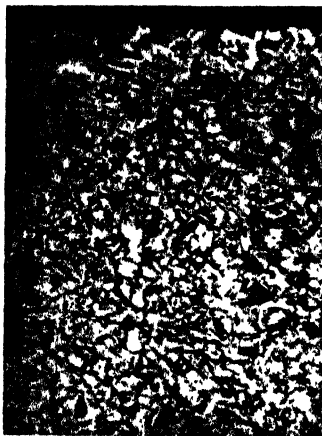


FIG. 86 ILLUSTRATING METHOD OF COPPER PLATING STEEL FOR PROTECTION PURPOSES 150
(Reduced one third in reproduction)

Flow Structure of Steel, etc.

It is frequently of importance, in connection with the stamping, pressing, forging, and general plastic treatment of steel, to be able to examine the lines of flow, or grain, of the metal. One of the commonest methods employed for this purpose is that of sulphur printing, which utilizes the effect of the small quantities of sulphur present upon silver bromide printing paper. In Baumann's method the surface to be examined is machined flat and

polished with emery paper No. 1. The silver bromide paper is soaked in very dilute sulphuric acid (about 1 to 3 per cent) solution in water, and is placed on the metal surface, the acid attacks the sulphides and liberates hydrogen sulphide, which acts upon and turns the silver bromide dark in colour. The auto-print is removed from the metal, washed, and then immersed in sodium hyposulphite to fix (or remove the excess bromide). The average period of time required is about 1 to 2 minutes.

Although the sulphur print method is convenient to employ it is known that local physical or even mechanical defects can influence the indications of the sulphur print. Further, phosphorus can also give rise to the evolution of gases, producing a dark stain on silver bromide paper. An improved method due to Van Roven and Ammermann,

* Cassel Cyanide Co.



FIG. 87 SULPHUR PRINT FROM FORGED AND STAMPED CRANKSHAFT, SHOWING SATISFACTORY GRAIN FLOW

known as "mercuric sulphur printing," consists in soaking a piece of thin silk with an acid solution of mercuric chloride and applying it to the polished and cleaned steel surface. Sulphide enclosures then cause a dark stain by the formation of mercuric sulphide, while the gas evolved from the phosphorus areas produces a yellow stain of mercuric phosphide. A further improvement is the use of a special

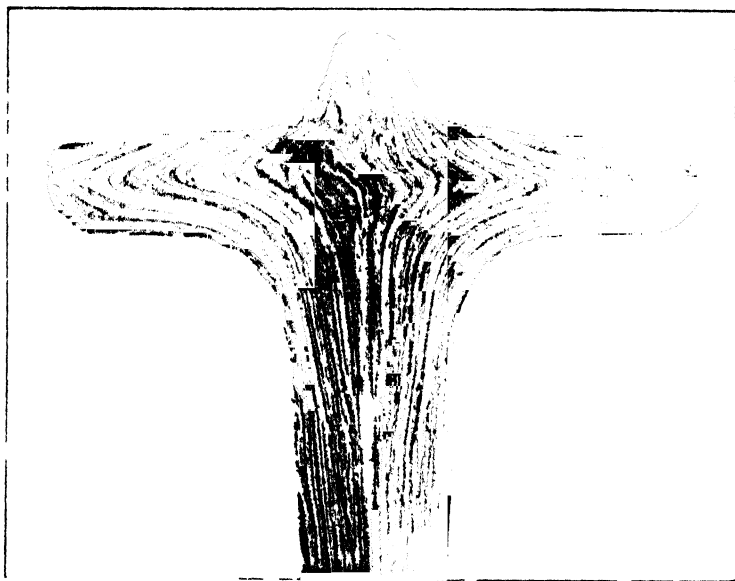


FIG. 88. VALVE STAMPING, SHOWING SATISFACTORY FLOW OF METAL

gelatine-coated paper in place of the silk, the paper being soaked in the reagent for a few minutes before applying it to the steel for 3 to 5 minutes, followed by gentle swabbing of the paper with cotton wool soaked in water.

Fig. 87* shows a typical sulphur print made from a section of a forged and stamped automobile engine crankshaft, that the method of manufacture is satisfactory is shown by the flow of the grain.

Another method often employed of obtaining macrographs showing grain flow consists in polishing the surface thoroughly and etching with a 10 to 20 per cent nitric acid solution followed by a copper reagent.

Figs. 88, 89 and 90 show the flow structures of stamped and

* Courtesy of the Institution of Automobile Engineers



FIG. 89. STEMMED HOLLOW HEAD VALVE IN ALLOY STEEL SHOWING FLOW OF METAL ALONG STEM



FIG. 90. VALVE TURNED FROM SOLID DRAWN BAR (UNSATISFACTORY FLOW STRUCTURE)

turned alloy steel valves for petrol engines; the difference between the stamped valves in Figs. 88 and 89 and the solid bar turned valve in Fig. 90 is marked.

Heat tinting is another method employed, which depends upon the colours of the oxides of the iron and the phosphorus content.

If polished sections are heated to a certain temperature the phosphorus-rich portions appear as yellowish-white streaks, and the purer metal as a blue background.*

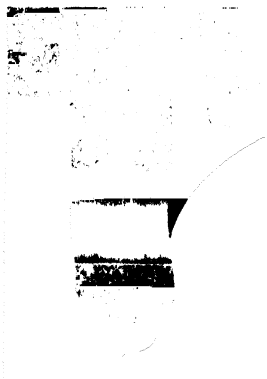


FIG. 91. MACROGRAPH OF
SAND CAST PISTON IN
HYDUMINIUM R.R. 53
ALUMINIUM ALLOY

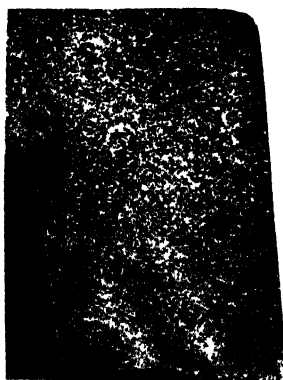


FIG. 92. MACROGRAPH OF
PISTON STAMPING IN
HYDUMINIUM R.R. 59
ALUMINIUM ALLOY

The macrostructure of aluminium alloys, such as R.R. alloys, is revealed by first polishing the section with various grades of emery down to No. 00, followed by buffing on a linen pad lubricated with polishing soap, after which it is cleaned with benzine ready for etching. The etching solution consists of 3 parts glycerine, 2 parts hydrofluoric acid, and 1 part nitric acid. This is applied to the surface with cotton wool, washed off after two minutes and renewed. The black deposit formed can be removed with cotton wool. The specimen is dried by washing with alcohol or boiling water.

Typical macrographs of sand-cast R.R. 53 alloy and stamped R.R. 59 alloy pistons are given in Figs. 91 and 92 respectively.

Steel Wire

Wire is made by the repeated process of drawing a rod of the material through a series of hard steel or tungsten carbide lined steel

* For fuller particulars, see *The Microscopic Analysis of Metals*, by Osmond and Stead.

dies; for example, a steel rod of $\frac{1}{4}$ in. diameter (or about 3 S.W.G.) can be drawn through tungsten steel dies so that it is reduced by about one gauge (S.W.G.) number at each draw, until its final diameter is about 0.040 in. (or 19 S.W.G.).

During the process of drawing the material becomes progressively harder and less ductile. For example, the tensile strength of a certain steel wire of 0.126 in. (about 10 S.W.G.) was found to be 88 tons per sq. in. with 2 per cent extension, whilst that of the same material wire of 0.040 in. (19 S.W.G.) was 125 tons per sq. in. with only 0.3 per cent extension.

The torsional strengths of the two wires were such that the thicker wire required 13.3 complete twists to break it, for a length of 5 in., whilst the thinner wire required 35.6 twists in the same length.

Fig. 93 shows how the tensile strength of plain steel aircraft wire varies with the amount of drawing—that is, with the gauge or diameter of wire.

The same diagram also shows the number of complete twists required to break wires of different diameters, and the number of bends through angles of 90° which the wires will withstand before fracturing.

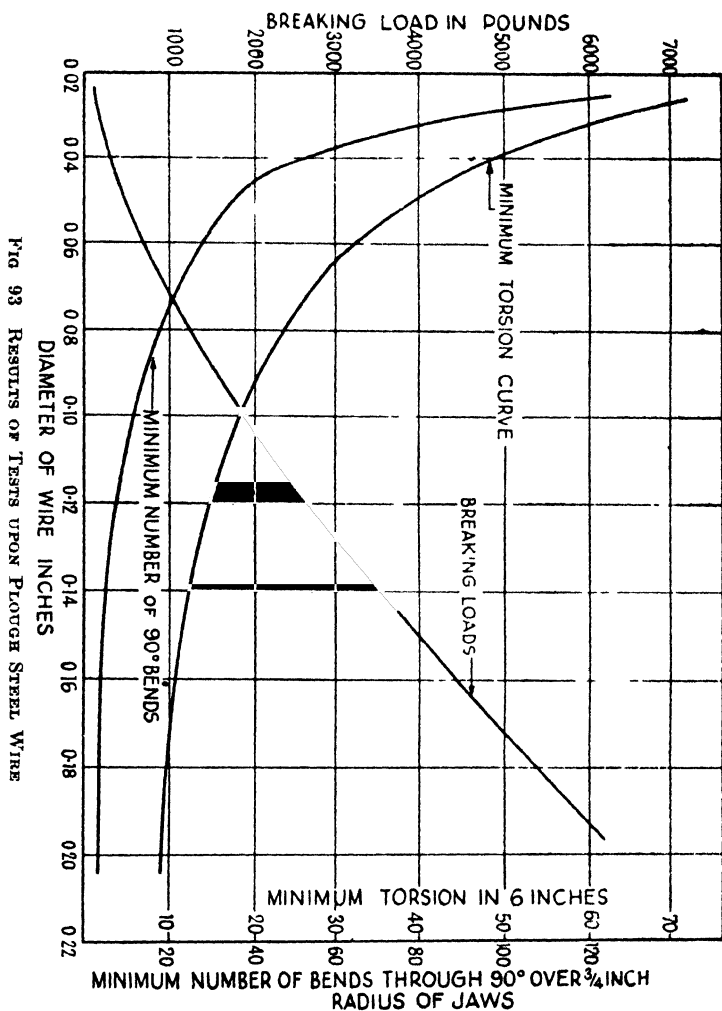
Microscopical examination of the internal structure of drawn steel wire has shown that it is desirable to obtain both pearlite and sorbite, and that the more sorbite present the tougher and stronger will be the wire, in attempting to obtain the maximum of sorbite there is, however, a risk of obtaining martensite and troostite, which tend to cause the wire to fracture during the drawing process.

Too rapid chilling after leaving the patenting furnace will promote the formation of sorbite and martensite; another cause of the presence of the latter constituents is that due to the frictional heat, during service or drawing, which causes the surface layers to be momentarily heated to redness, usually followed by a chilling effect, which leaves the surface layers in the martensitic condition and causes the wire to break when bent; the failure of wire ropes is often due to this cause.

Another source of failure is that due to the use of badly designed pulleys, in which the surface of the crown wires spreads out, with the result that the surface layers become brittle and fracture; this fracture travels progressively through the other wires.

Piano or Music Wire. This is usually made from a medium-carbon steel in sizes varying from about 16 S.W.G. (0.064 in.) up to about 28 S.W.G. (0.0148 in.).

The following is a typical percentage analysis of the steel used: C, 0.60; Mn, 0.43; Si, 0.09; S, 0.02; P, 0.02.



The tensile strength of this wire varies from 100 to 160 tons per sq. in. for the above-mentioned sizes.

Wire made from a crucible cast steel of high quality usually goes by the name of *plough steel* wire, this wire, which is made in all gauges from about 10 S.W.G. (0.128 in.) up to 28 S.W.G. (0.0148 in.), is used for flexible and stranded wire cables, and similar purposes.

The following is a typical percentage analysis of plough steel wire: C, 0.85; Mn, 0.60; Si, 0.14; P, nil; S, 0.01; Cu, 0.03.

The tensile strength of this wire varies from about 90 to 160 tons per sq. in.

It is usually made in different qualities, or grades, according to the purpose for which it is required.

The following table shows a typical method of grading plough steel wire—

TABLE 37
GRADES OF PLOUGH STEEL WIRE

Grade	Tensile Strength Tons per sq. in.	Average Elongation per cent
A	140 to 160	0.4
B	130 to 140	1.2
C	120 to 130	2.0
D	110 to 120	2.8
E	100 to 110	3.6
F	90 to 100	4.4
G	80 to 90	5.2

The grades most used in aircraft work are D and E. It is usual to galvanize or electro-plate these wires with nickel. Table 38 gives the strength and weight of plough steel wires, as used in various types of aircraft. The strengths are given for (a) a constant tensile strength of 100 tons per sq. in., and (b) tensile strengths varying from 60 tons per sq. in. for 4 S.W.G. wire up to 140 tons per sq. in. for 30 S.W.G. wire; the latter values are approximately those obtained in wire drawing.

Fine Wires. Wires of small diameter of carbon or alloy steel of from 0.040 in. down to 0.002 in. diameter are made by drawing through hard diamond or sintered carbide dies, whilst copper wires are usually drawn through chilled cast-iron dies in steps of about 1 S.W.G. at a time.

Alloy Steel Wires. Alloy steels can be used for wire-drawing, but are not employed to any great extent, as the same results can usually be obtained with carbon steel wires.

TABLE 38
SIZES, WEIGHTS, AND STRENGTHS OF PLOUGH STEEL WIRE

S.W.G.	Diameter		Sectional Area Sq. in.	Weight in Pounds		Breaking Load in Pounds		
	Inches	mm.		100 Yards	1 Mile	At 100 Tons per sq. in.	At Tons per sq. in.	Lb.
7 0	0.500	12.7	0.1963	193.4	3404	43,975	—	
6 0	0.464	11.8	0.1691	166.5	2930	37,854	—	
5/0	0.532	11.0	0.1466	144.4	2541	32,820		
4 0	0.400	10.2	0.1257	123.8	2179	28,144		
3/0	0.372	9.4	0.1087	107.1	1885	24,350		
2 0	0.348	8.8	0.0951	93.7	1649	21,300		
0	0.324	8.2	0.0824	81.2	1429	18,464		
1	0.300	7.6	0.0707	69.6	1225	15,830		
2	0.276	7.0	0.0598	58.9	1037	13,400		
3	0.252	6.4	0.0499	49.1	864	11,170		
4	0.232	5.9	0.0423	41.6	732	9,470	60	5680
5	0.212	5.4	0.0353	34.8	612	7,900	65	5140
6	0.192	4.9	0.0290	28.5	502	6,490	70	4550
7	0.176	4.5	0.0243	24.0	422	5,450	75	4180
8	0.160	4.1	0.0201	19.8	348	4,500	80	3600
9	0.144	3.7	0.0163	16.0	282	3,650	85	3100
10	0.128	3.3	0.0129	12.7	223	2,880	90	2590
12	0.104	2.6	0.0085	8.4	148	1,900	95	1800
14	0.080	2.0	0.0050	5.0	88	1,130	100	1130
16	0.064	1.6	0.0032	3.2	56	720	105	756
18	0.048	1.2	0.0018	1.8	32	406	110	446
20	0.036	0.9	0.0010	1.0	18	228	115	262
22	0.028	0.7	0.000615	0.610	10.7	138	120	166
24	0.022	0.56	0.000380	0.375	6.6	85.5	125	107
26	0.018	0.46	0.000250	0.250	4.4	57.0	130	74
28	0.0148	0.37	0.000172	0.168	3.0	38.6	135	52
30	0.0124	0.31	0.000121	0.119	2.1	27.2	140	38

Non-corrodible steel wire containing from 25 to 30 per cent of nickel, and from 0.30 to 0.45 per cent of carbon, is used for hawsers, cables, and netting for sea-water use. The tensile strength of 12 S.W.G. (about $\frac{1}{16}$ in.) nickel-steel wire is about 90 tons per sq. in., with an elongation of 6 per cent in 2 in., and an area contraction of 16 per cent.

Stainless steel wire is available commercially in sizes from 0.002 to 0.500 in. diameter in various qualities, e.g. hard drawn, mild drawn, and soft descaled, in plain or polished condition.

The steel can be supplied in coils for the smaller sizes and in rods of 14 to 16 ft. for the larger diameters.

Other Types of Steel Wire

A large quantity of steel wire is now used for *welding purposes*, in the form of straight lengths or coils. In addition alloy steel wires are made for welding alloy steels such as manganese, nickel, and nickel-chrome ones. Swedish iron wires are also made for welding.

Mild steel rivet wire and wire for cold heading is another grade which is made in sizes from 15 S.W.G. to 0.5 in. in 0.08 to 0.12 per cent carbon steel. Alloy steel wires for rivet-making purposes are also available.

Ball bearing steel wire is usually of the 0.3 to 0.4 per cent carbon and 1.0 per cent chromium grade. It is used for making both ball and roller bearings.

Spring steel wires in 1.0 per cent carbon and in alloy steels are widely employed for petrol engine valve springs and for numerous other purposes. The wires are usually ground or shot-blasted before making into springs, to avoid fatigue crack effects.

Some other grades of steel wire are used for making needles, fish-hooks, knitting needles, gramophone needles, and for a variety of wire shapes, in low to high carbon grades.

Wire gauze for sieves and screens is another instance of the use of steel wires.

Steel Cables

In all cases in which a high tensile strength wire (combined with a certain degree of flexibility) is required, it is necessary to employ not a single plough steel wire, but a cable or rope made up of a number of smaller wires of plough steel twisted together, so as to form a spiral circular rope.

The construction and sizes of steel cables vary considerably according to the purpose for which they are required, from the fine 19-wire single-strand Bowden cable of $\frac{1}{16}$ in. diameter, with a breaking load of about 6 cwt., up to the marine hawser cable, consisting of a 3-in. outside diameter rope, composed of 6 strands each of 37 wires, with a breaking load of about 300 tons. Cables of 9 in. diameter and above are made for marine salvage work, and up to 3 ft. in diameter for suspension bridges.

Strength of Cables. The strength of a steel cable is invariably less than the net strength of the individual wires; the efficiency of a cable is expressed by the ratio of the actual to the net breaking strength of the total wires, and varies from 70 to 85 per cent.

The weight and strength increase approximately as the diameter of the cable, provided that the construction is the same; more exactly the weight and strength increase at a slightly higher rate.

TABLE 39
STRENGTHS OF WIRE CABLES

Description	Tensile Strength Tons per sq. in.	Torsions in 100 Diameters					
		Black		Galvanized			
		A	B	Smaller		Larger	
				A	B	A	B
Mild patent steel	60-70	34	26	28	21	23	17
Patent steel	70-80	34	26	28	21	23	17
Best patent steel	80-90	34	26	28	21	23	17
Special imperial patent steel	90-100	34	26	28	21	23	17
Best plough steel	100-110	32	24	23	17	19	14
Special imperial plough steel	110-120	30	23	15	11	11	8
	115-125	28	21	10	8	7	

[K.]

TABLE 40
PROPERTIES OF STEEL CABLES OF DIFFERENT SIZES

Size Circumference	Di- ameter	Approxi- mate Weight per Fathom	Crush- ible Steel	Best Selected Improv- ed Steel	Best Selected Mild Plough Steel	Best Selected Extra Plough Steel
Inches	Inches	lb.	B.S. Tons	B.S. Tons	B.S. Tons	B.S. Tons
1½	½	17½	4½	47½	52½	57½
1½	½	2½	6	6½	72½	77½
1½	¾	32½	82½	87½	95	10½
2	¾	4	11	117½	127½	142½
2½	1½	52½	142½	15	16½	18
2½	1½	62½	17½	182½	20	22½
2½	1½	77½	212½	22½	247½	272½
3	1½	9	247½	26½	29	317½
3½	1½	10½	297½	317½	35	38
3½	1½	13	34½	367½	402½	442½
3½	1½	14½	395	42	46	507½
4	1½	16½	455	48½	53	58
4½	1½	177½	52½	56	61½	67
4½	1½	20	575	61	67	73
4½	1½	22	65	69	76	83
5	1½	25	72	76	83	92

[Bilvaunt & Co. Ltd.]

In regard to steel cables or wire ropes used for general engineering purposes nine different kinds are specified by the British Standards Institution and the tensile strength and torsion tests for these are laid down.

Particulars of typical wires used in the construction of cables are given in Table 39. In connection with the values for torsion these are in accordance with the British Standard Specifications for 100 diameters. The figures given in column A are for the original wire before it is made into cable, and those in column B for wire unstranded from the cable; the torsional strengths are naturally lower in the latter instances. The unstranded wire is required to possess a strength not less than the lower limit of its range and, if its diameter exceeds 0.036 in., not in excess of the upper limit by more than 5 tons per sq. in.

Aircraft Wires and Cables

The wires used for bracing purposes on aircraft include (1) high-tensile steel swaged rods, made to B.S.S. 5W8, for internal bracing, and (2) high-tensile streamline wire, made to B.S.S. 5W3, for external bracing. In the case of light aircraft high tensile steel wire with ferrule ends, to B.S.S. 3W1, is sometimes used.

The air resistance of streamline wire of elliptical section is only about one-sixth that of round wire of diameter equal to the width of the smaller axis of the ellipse, the fineness ratio being about 5 : 1. The streamline wire is made from round rod by swaging. Usually the ratio of length to major diameter is limited to 100 : 1 in order to reduce the possibility of failure by fatigue.

The sizes of streamline wire vary from No. 4 B.A., with a width of 0.192 in. and thickness of 0.048 in. and breaking load of 1050 lb., up to the $\frac{5}{8}$ -in. size with a width of 0.924 in. and thickness of 0.231 in. and breaking load of 24,700 lb. For special purposes larger sizes are made up to 1 $\frac{1}{4}$ in. with a width of 1.928 in. and thickness of 0.482 in. and breaking load of 103,000 lb. These values correspond to tensile strengths of about 66 tons per sq. in.

Aircraft cables of the *extra-flexible type* used for the control system where they may have to pass over pulleys are made of sections of 7 strands of 4, 7, 19, or 37 wires each; the diameters of the wires range from 0.075 in. up to about 0.305 in., with breaking strengths of 650 and 11,000 lb. respectively; for the main control cables a minimum breaking strength of 10 cwt. is usually specified. Cables for this purpose are specified in B.S.S. 3W2.

Kite balloon cable usually has a soft core of hemp fibre and is specified in B.S.S. 3W6. *Straining cable* is specified in B.S.S. 3W2 also.

Steel Tubing

Steel tubing for engineering purposes falls into three principal classes, namely, as follows: (a) *Weldless* or *Seamless*; (b) *Welded* and (c) *Open Seamed* or *Conduit*.

The tubing of class (a) is produced from a hollow billet by drawing or rolling. It is of uniform structure and thickness. Class (b) is made by bending or rolling strips of steel to a circular or any other section and welding the junction. Class (c) is made in a manner similar to the preceding, but is not welded, it is employed in cases where the tubes are lightly loaded such as for electric wire conduits and ornamental purposes.

Seamless tubing can be produced in both carbon and alloy steels, and on account of the absence of joints is of uniform strength.

Welded tubing possesses the advantage that a more uniform wall thickness can be obtained, free from drawing marks, and it is not subjected to the disadvantages which often occur in the case of drawing and length rolling processes, it is usually only possible, however, to employ welding steels such as low- and medium-carbon and low-nickel steels. The process of manufacturing welded tubing is quicker and less expensive than that of drawing or rolling, but the strength of the welded joint is rather an uncertain quantity; this class of tubing is not generally employed for aircraft work.

In the case of certain mild steels, the tubing is often first made by welding the rolled plate with an electric arc which can travel along at a uniform rate, and the welded tube is then drawn through dies in the ordinary manner, very satisfactory results are thus obtained and the method is applicable to non-ferrous metals, such as brass but using a brazing process instead of welding.

Steel tubing is made from carbon and also alloy steels, and the strength properties in general are similar to those of drawn or extruded rods.

Carbon steel tubes are made of mild steel with 0.10 to 0.25 per cent carbon and medium-carbon steel of 0.30 to 0.55 per cent carbon.

The tensile strength of mild steel tubing varies from about 28 to 32 tons per sq. in. as drawn, with yield points of 25 to 28 tons per sq. in. Medium-carbon steel tubes give values for the yield point of 27 to 30 tons per sq. in. and tensile strength of 33 to 37 tons per sq. in. respectively. The tensile strengths of the annealed material are about 20 and 26 tons per sq. in., with yield points of 11 and 16 tons per sq. in. respectively, for the mild and medium-carbon grades of steel.

The tensile strength of tubes of the same billet material is **greater** for the smaller diameter tubings, owing to the greater hardening effect

due to rolling; the variation in strength between a 2-in. and a $\frac{3}{4}$ -in. tube may exceed 25 per cent when reckoned upon that of the larger tube.

The results* of tension tests given in Table 41 refer to steel tubing containing 0.35 per cent of carbon and 0.65 per cent of manganese. It will be observed that the average strength and elongation are less for the thinner tubing, in general, when the tubing thickness is reduced below about one-twentieth of the external diameter, the strength is reduced in proportion to the thickness.

TABLE 41
TENSION STRENGTH OF CARBON STEEL TUBING

Diameter in Inches	Thickness of Wall Inches	Yield Point Tons per sq. in.	Tensile Strength Tons per sq. in.	Elongation per cent in 8 in.
1.180	0.031	32.6	38.0	15.6
1.180	0.031	36.5	40.6	15.8
0.986	0.019	32.8	43.4	13.8
0.986	0.019	31.0	36.3	13.4
0.884	0.009	33.0	36.7	12.9

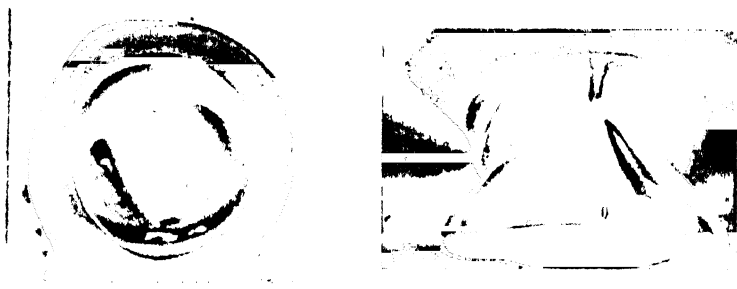


FIG. 94. RESULT OF CRUSHING TEST ON MILD STEEL TUBING SPECIMENS.

It is now usual to specify a *crushing test* for mild steel tubing—namely, that the specimen to be tested, of length equal to $1\frac{1}{2}$ times the outside diameter, should withstand endwise crushing until its length is decreased by from $\frac{1}{3}$ to $\frac{1}{2}$ of its original value, or until the outside diameter is increased in one zone by 25 per cent; or until one complete fold is formed, without splitting or cracking.

* Columbia University Testing Laboratory

Steel tubing is usually supplied in lengths up to 16 ft. and, apart from any sagging effects due to weight, should be specified to be straight to within 1 in 600. The difficulties of annealing and heat-treating long lengths of tubing which in the ordinary way would necessitate subsequent restraughtening have been satisfactorily overcome by clamping the tube firmly in a vertical position between electric terminals. When a current is passed through the tube it is heated to the correct temperature for the material, and the tube is then automatically released by the terminals, when it drops into a vertical cylinder containing the quenching liquid. This method, which can be applied to both carbon and alloy steels, does not necessitate restraughtening. The permissible variation in the outside diameter of seamless tubing is usually stipulated as being ± 0.003 in. for tubes under $1\frac{1}{2}$ in. outside diameter, and ± 0.005 in. for those over $1\frac{1}{2}$ in.

The wall thickness should not vary more than ± 8 per cent or $- 3$ per cent.

The results of tests made upon $3\frac{1}{2}$ per cent nickel and 4 per cent nickel, with 1.1 per cent chromium, tubes show that thin-walled tubes do not develop the maximum strength values of the material when the wall thickness is less than 5 per cent of the wall diameter. Thin-walled tubes, which should from purely theoretical considerations give the maximum strength for weight, in practice give much lower values owing to failure by local deformation or buckling and not as thick-walled struts; moreover, they are more liable to weakening by corrosion effects on their inner surfaces unless special precautions against these are observed.

The results of some tests made upon $3\frac{1}{2}$ per cent nickel steel of about 1.18 in. outside diameter and in thicknesses ranging from 0.022 to 0.096 in., given in Table 42, show how the transverse bending, tensile and torsional strengths increase with the wall thickness.

Standard Tubing for Automobile Purposes

Four different classes of steel are specified for automobile tubing in the British Standard Specification No. 5009, namely, as follows: (1) Low-carbon steel; (2) medium-carbon steel; (3) high-carbon steel; and (4) high-carbon nickel steel.

The specifications contain a number of general clauses relating to the manufacture, heat-treatment, general definitions, mechanical tests, provision of samples, preparation of test pieces, workmanship, finish, and margins of manufacture. The composition limits and mechanical properties are laid down. The mechanical tests include specified minimum values for the yield point and ultimate tensile strength, a flattening and crushing test in the case of (1) and (2).

TABLE 42
PROPERTIES OF 3½ PER CENT NICKEL STEEL TUBES
(A) TRANSVERSE BENDING AND TENSION TESTS

Specimen No.	Transverse Bending		Tension	
	Fibre Stress at Elastic Limit Tons per sq. in.	Maximum Fibre Stress Tons per sq. in.	Fibre Stress at Elastic Limit Tons per sq. in.	Maximum Fibre Stress Tons per sq. in.
1	20.6	30.5	25.7	37.2
2	30.8	36.9	30	46.0
3	38.3	37.2	36.0	44.9
4	34.8	60.8	34.2	52.1
5A	42.1	62.3	33.8	52.4

(B) TORSION TEST

Specimen No.	Tube Diameter Inches	Thickness of Walls Inches	Fibre Stress at Elastic Limit Tons per sq. in.	Maximum Fibre Stress Tons per sq. in.	Modulus of Rigidity Tons per sq. in.
1	1.180	0.022		17.3	4420
2	1.180	0.040	17.5	23.6	5180
3	1.182	0.061	18.3	27.3	5230
4	1.184	0.076	22.2	33.0	4910
5A	1.185	0.096	19.4	33.8	5310

Table 43 illustrates the principal requirements of the four classes of steel tubes as specified.

TABLE 43
STANDARD TUBING FOR AUTOMOBILE PURPOSES

Class of Steel Tube	Chemical Compositions (per cent)						Mechanical Properties Tons per sq. in.	
	C	Si	Mn	Ni	S	P	Tensile Strength	Yield Point
Low carbon steel	0.10-0.20	max. 0.25	0.30-0.70		max. 0.05	max. 0.05	28	26
Medium carbon steel	0.28-0.40	0.25	0.30-0.70		0.05	0.05	35	28
High carbon steel	0.45-0.55	0.25	0.30-0.70		0.05	0.05	45	38
High carbon nickel steel	0.30-0.40		0.35-0.65	2.75-3.50	0.05	0.05	45	38

The tubes for the mechanical tests may, at the discretion of the manufacturer, be delivered either in the drawn or blued condition. It is further pointed out that if blued tubes are annealed, brazed, or welded their strength values may be reduced at the parts where they are so treated to certain specified minimum values, as shown in Table 44.

TABLE 44
BRITISH STANDARD TUBING FOR AUTOMOBILE PURPOSES

Mechanical Properties	Low carbon Steel	Medium carbon Steel	High-carbon Steel	High-carbon Nickel Steel
Tensile strength (min.) tons per sq. in.	20	26	33	37
Yield point (min.) tons per sq. in.	11	16	22	24

The flattening test specified is as follows:

(a) *For Low and Medium-carbon Steels.* Samples of the tubes to be flattened at the ends, or at any point where defective material is suspected, by a few blows (not more than six) until the sides are three times the thickness of the metal apart, or two-thirds the original bore, whichever is the smaller, without showing signs of cracking.

(b) *For High-carbon and High-carbon Nickel Steels.* Samples of the tubes to be flattened at the ends, or at any point where defective material is suspected, by a few blows until the sides are eight times the thickness of the metal apart, or two-thirds the original bore, whichever is the smaller, without showing signs of cracking.

The crushing test for the two former steels specifies that samples of the tubes are to be crushed endwise until the outside diameter is increased in one zone by 25 per cent or until one complete fold is formed, without showing signs of cracking. The length of the sample should be about one and a half times the outside diameter of the tube.

Other Alloy Steel Tubing

It is now possible to obtain commercial tubing of high tensile strengths for automobile and aircraft purposes in a wide range of alloy steels and in the round and numerous other sections for specific purposes. These steels include nickel, nickel-chromium, chromium, stainless, etc., of the weldless or solid-drawn types to standard specifications.

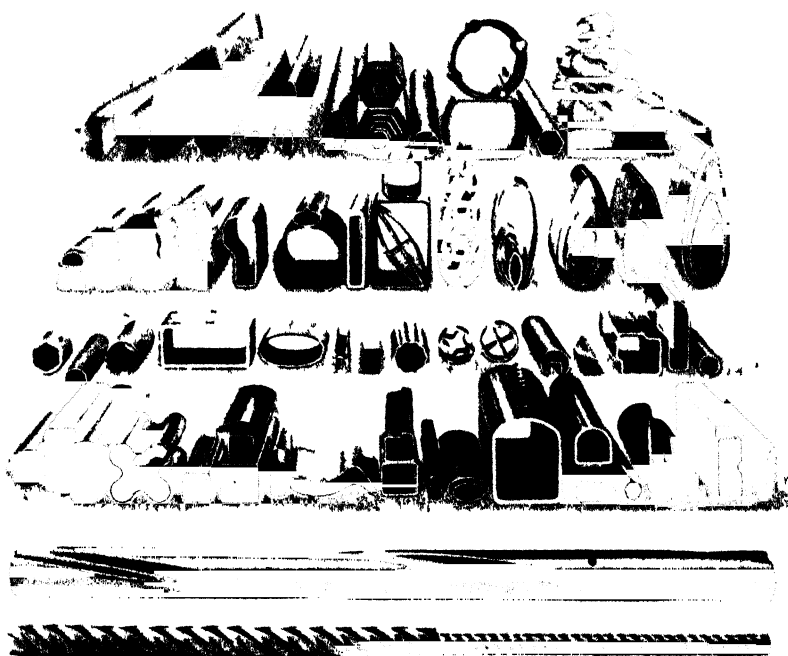


FIG. 95. EXAMPLES OF MODERN TUBE SECTIONS IN PLAIN AND ALLOY STEELS (AYLES AND POLLOCK, LTD.)

The test results upon some typical alloy steels made by Messrs Vickers-Armstrongs Ltd are given in Table 45 (p. 190).

It should be noted in Table 45 that the percentage elongations given by a tubular tensile test piece depend upon the gauge, length, and diameter of the tube tested and therefore may differ considerably from that given by a standard 2 in. by 0.564 in. tensile test bar.

Notes on Steel Tubing

The properties of steel tubing under alternating stress conditions can be investigated by means of a machine resembling the Wohler type, whilst for shock tests the falling weight impact type of machine is convenient.

TABLE 45
TENSILE TESTS ON ALLOY STEEL TUBES

Type of Steel	Symbol	Yield Tons per sq. in.	Max. Stress Tons per sq. in.	Elonga- tion per cent on 2 in. of Tube	Size of Tube Tested
Air-hardening Nickel-chrome	SHNC	85.2 74.0	103.9 89.0	12.5 12.0	80 mm. \times 7G 2½ in. \times 14G
Nickel chromium	VACS	56.0 54.5	64.4 60.9	22.0 7.0	2½ in. \times 1½ in. 3½ in. \times 17G
Nickel	3 NS	46.5 44.4	52.4 56.0	25.0 21.5	1½ in. \times 2G 1 in. \times 10G
High chromium stainless	Immaculate	36.0	43.3	17.0	2½ in. \times 18G

The results of a series of tests made upon steel tubing and tube sockets and liners may be briefly enumerated as follows—

1. The effect of drilling a small hole in a tube, which is alternately stressed nearly up to its elastic limit, is to weaken the tube considerably; the undrilled tube is stated to have from 10 to 20 times the life of the drilled tube. Where drilling is necessary, the tube should be properly reinforced with a liner or sleeve. Hard tubing is affected to a much more marked extent than annealed tubing.

2. Lugs intended for connecting pieces of tubing with brackets, fittings, or other members, whether of the sleeve or liner type, should be tapered off towards the outlet, as shown in Fig. 96. If left parallel, there is a serious weakening due to the abrupt change of section, together with want of resilience at the socket portion.

3. For beams of the cantilever type, tapered tubes are preferable to uniform ones, owing to their greater resilience and lighter weight for the same strength. Alternating tests made on a Wohler type of machine, at 400 r.p.m., on 1 in. by 20 S.W.G. (0.036 in.) steel tubing, proved that whereas two parallel tubings broke at 20,585 and 30,390 revolutions respectively, yet when tapered tubes, tapering by ½ in. per foot, were employed, of the same thickness, they broke at 23,557 and 32,225 revolutions respectively.

Each of the tubes was loaded with 111.56 lb. at a distance of 12.75 in. from the grips, which was equivalent to a stress of about 25 tons per sq. in.

Tapering in thickness, as distinct from tapering in diameter, has been shown to be both economical and beneficial. An instance of this is in the case of motor-cycle front-forks, which, when made from 19 S.W.G. tubing, invariably broke off where they were brazed to the crown. Increasing the thickness to 18 and 17 S.W.G. respectively failed to prevent these breakages. When, however, tubes tapering from

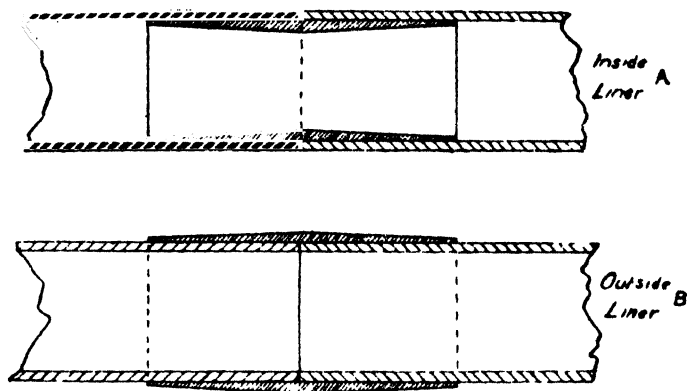


FIG. 96 LINERS FOR TUBULAR JOINTS

19 S.W.G. at the crown to 22 S.W.G. at the bottom ends were employed, the trouble was completely overcome: the increased resilience no doubt accounted for this effect.

4. Tubular liners should preferably be soft soldered in place. Tapered sleeves are satisfactory, the outer end thickness should be less than that of the tube itself. Sleeves or liners which are merely pressed into position are not satisfactory, soldering or brazing should be resorted to in every case. Tests made upon similar 1 in. by 20 S.W.G. tubes—(a) drilled, but without a sleeve: (b) drilled, but with a sleeve pressed on: and (c) drilled, but with a similar sleeve soldered on, the sleeves in each case being $2\frac{1}{2}$ in. long by 18 S.W.G., and placed over the holes—gave the following results—

(a) Plain drilled tube	3,684 rev. before fracture.
(b) Pulled tube, with pressed sleeve	9,320 „
(c) Pulled tube, with soldered sleeve	48,687 „

5. Where sockets are employed, the tube should be either brazed or pinned and soldered. The results of tests upon soldered joints show that there should be about 0.005 in. clearance between the tube and socket diameters, as a maximum value, and that smaller clearances give as good results. The shearing stress of a good soldered joint may

be taken as being about $2\frac{1}{2}$ tons per superficial inch. With a solder socket joint it is possible to make the tensile strength of the joint at least equal to that of the tube.

6. For tubular members under stress soft soldering is recommended in preference to brazing or welding, as the temperatures of the process are low enough not to affect the hardness of the metal, especially in the case of alloy and hard drawn steel tubes.

Hard soldering, or silver soldering, gives a stronger joint, and the temperature of the operation is lower than for brazing, but much higher than for soft soldering. Brazing is not recommended for tubular structures which have to take stresses, or for medium thicknesses of tubes. It is, however, applicable to tubes of appreciable wall-thickness which have to take torsional stresses.

7. Stainless steel tubing is now employed for exhaust manifolds and pipes of aircraft engines, the joints being welded. A typical example of an exhaust manifold is the circular form used on radial air-cooled aircraft engines. Flexible stainless steel tubing is another more recent innovation: commercial tubing of this type is used on certain American aircraft.

CHAPTER V

ALLOY STEELS

WHILST the carbon steels previously considered all contain small percentages of other elements, namely, manganese, silicon, phosphorus, and sulphur, the name "alloy steel" is generally applied to steels containing, in addition, other elements, such as nickel, chromium, vanadium, molybdenum, etc. Similarly, carbon steels with appreciably greater proportions of silicon come into the alloy steel group under the heading of *silicon steels*. In the same way, carbon steels containing greater proportions of manganese, up to about 14 per cent, are included under the heading of *manganese steels*.

The addition of even small percentages of certain alloying elements, such as nickel, chromium, molybdenum, and vanadium, imparts important mechanical and physical properties to steels of given carbon content; the individual effects of these elements upon the properties of the steels are considered later in this chapter. Boron, copper, and lead are also used for special alloy steels. The principal alloying elements associated with the special steels under consideration are given in Table 46, and in this connection only a relatively small number of elements adjacent to iron in the periodic system possess the property of forming useful alloys with iron. These metals have high melting-points and possess a very similar degree of crystal symmetry—namely, that of body-centred or face-centred cubes.

TABLE 46
METALS EMPLOYED IN ALLOY STEELS*

Metal or Element	Group No.	Atomic No.	Atomic Weight	Melting point, °C.
Iron	VIII	26	55.85	1535
Nickel	VIII	28	58.68	1452
Cobalt	VIII	27	58.97	1478
Tungsten	VIa	74	184.00	3267
Molybdenum	VIa	42	96.00	2450
Chromium	VIa	24	52.00	1525
Vanadium	VA	23	51.00	1720
Manganese	VIIa	25	54.93	1260

* "Alloy Steels," H. C. H. Carpenter. Cantor Lectures, *Royal Society of Arts*, 1927-8.

The simplest alloy steel, known as a *Ternary Steel*, is composed of three elements—namely, iron, carbon, and the alloying element; the latter may be nickel, chromium, tungsten, or manganese.

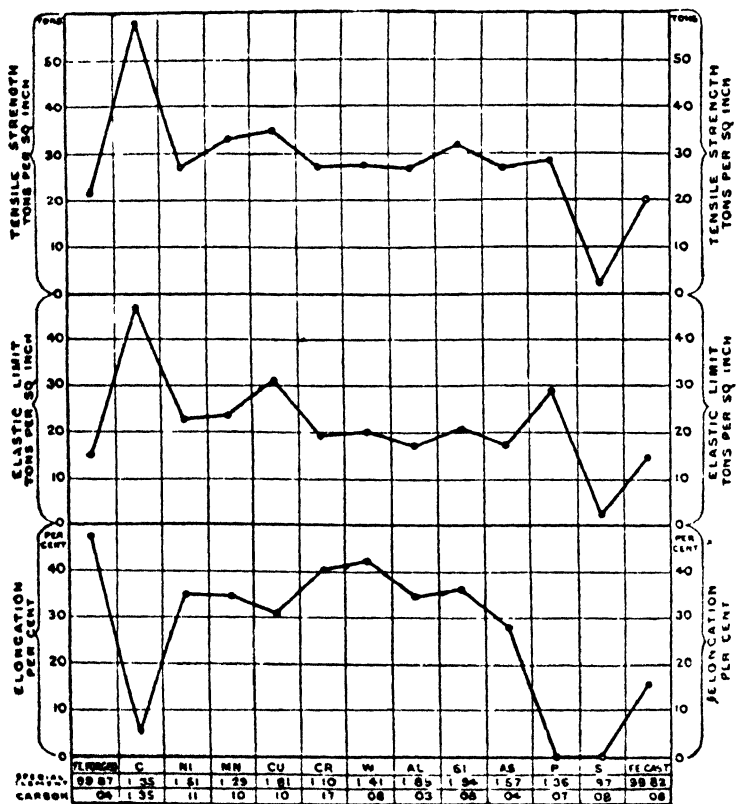


FIG. 97 ILLUSTRATING THE EFFECTS OF VARIOUS ELEMENTS UPON THE PROPERTIES OF IRON. (ARNOLD)

When two alloying elements are present, in addition to iron and carbon, the steel is known as a *Quaternary Steel*. Included in this class are nickel-chromium, chrome-vanadium, and cobalt-chromium steels.

Steels containing three or more alloying elements are known as *Complex Steels*, certain of the high-speed tool steels fall into this category, whilst heat-resisting steels containing nickel, chromium, tungsten, and silicon are also included.

In regard to the effects of special elements in ternary alloy steels,

it is possible to trace a more or less definite relation between the percentage of the special element and the percentage of carbon.

In this respect, reference may be made to the work of Guillet, who showed that the effect of increasing either the percentage of carbon or that of the alloying element in a ferrary steel *was to change the structure of the steel* from a *pearlitic* to a *martensitic*, *austenitic*, or even *cementitic* nature. The greater the percentage of carbon, the smaller the proportion of the special element needed to produce a given change of structure and, conversely, the higher the percentage of the special element, the lower the percentage of carbon required.

The results of a series of tests upon thirteen iron alloys, made by Professor Arnold,* are given graphically in Fig. 97.

The alloys in question included cast and forged pure iron, and also iron alloys containing, respectively as nearly as possible $1\frac{1}{2}$ per cent carbon, silicon, aluminium, manganese, nickel, copper, chromium, tungsten, arsenic, phosphorus, and sulphur. The investigation included an important series of mechanical and microscopical tests upon the alloys produced. The tests do not show the effects of wide variations in the percentages of each element, but nevertheless they afford a most interesting comparison of the results produced by the same percentage of different elements.

The following results show the effect of certain elements upon the mechanical properties of steel of 0.30 per cent carbon content in the non-heat-treated condition

TABLE 47
EFFECT OF DIFFERENT ELEMENTS UPON THE PROPERTIES
OF 0.30 PER CENT CARBON STEEL

Other Elements Present	Yield Point Tons per sq. in.	Tensile Strength Tons per sq. in.	Elongation on 2 in. per cent	Reduction of Area per cent
Pure 0.30 per cent carbon steel	17	20	30	55
With 3 per cent nickel	24	42	24	45
With 3.5 per cent nickel and 0.75 per cent chromium	43	52	17	45
With 1.3 per cent chromium and 0.18 per cent vanadium	44	55	16	45
With 12.0 per cent chromium	38	48	20	47

* "The Physical Influences of Elements on Iron," Arnold (*Proc. Iron and Steel Institute*, 1894).

By heat-treating these steels their mechanical properties can be varied over a very wide range as compared with plain carbon steels.

In general, as the percentage of carbon in alloy steels increases, so do the yield point and tensile strength increase and the elongation decrease.

The maximum percentages of carbon, namely, 0.7 to 1.5, occur in high-speed tool steels.

Almost all of the modern alloy steels used for purposes other than tool steels contain below about 0.45 per cent of carbon.

Effects of Various Elements on Steel

Having seen the general effects of certain elements upon the properties of steel, the individual influences of the more important elements will now be considered in greater detail, commencing with nickel.

Nickel. The effect of nickel upon the constitution of steel has been dealt with from the metallographical side in Chapter II, and it was there shown that at normal temperatures nickel is in solid solution in the iron and that after slow cooling nickel steel may have pearlitic, martensitic, or austenitic structure, according to its nickel and carbon contents.

The general effects of nickel may be summarized* as follows--

The pearlitic nickel steels have a low critical range, respond readily to heat-treatment, and reduce the danger from scaling and warping to a minimum.

In the pearlitic range, also, *nickel increases the tensile strength and yield point* of steel. In the annealed condition the average effect of nickel in amounts up to 8 per cent may be stated as follows--

Each 1 per cent nickel

Increases the elastic limit by 1.8 tons per sq. in.

Increases the tensile strength by 1.9 tons per sq. in.

Increases the reduction of area by 0.5 per cent.

Decreases the elongation by 1 per cent.

On the other hand, it is in the heat-treated conditions that the presence of nickel in steel shows its greatest value, the strength, yield point, and hardness being raised without a corresponding loss in ductility as compared with a carbon steel.

That nickel also increases the toughness of the steel is shown by the higher impact values obtained.

Nickel tends to *retard the grain growth* in steel, resulting in a wide range of heating without damage to the steel, or it may be maintained above the critical range for long periods of time without great damage.

* Bureau of Information on Nickel.

Another effect, somewhat related, is the tendency on slow cooling to maintain a fine-grain pearlite or sorbite instead of full lamellar pearlite.

The addition of nickel to annealed carbon steel apparently strengthens the ferrite, with the result that the *endurance ratio* is raised. The full effect of nickel on the endurance ratio, however, is obtained only by quenching and tempering.

The austenitic high-percentage (20-30) nickel steels possess excellent corrosion-resisting properties and also resistance to oxidation at high temperatures. They are practically non-magnetic. Steels with different coefficients of expansion are produced by varying the nickel content.

The properties of the more important commercial steels are considered later in this chapter.

Chromium. This element occurs either singly or in combination with other special elements such as nickel, molybdenum, vanadium, etc., in commercial steels. The effect of chromium upon the constitution of steel is considered in Chapter II and may be summarized, briefly, by stating that it differs from that of nickel, since it forms a double carbide, resulting in greater strength and hardness in a heat-treated steel. By the use of both these elements in steel a double effect is obtained because the nickel strengthens the ferrite matrix and the chromium strengthens the carbide constituent, giving better physical properties than when either element is used by itself.

In carbon steel, chromium raises more or less uniformly both the Ac. 1 and the Ac. 3 points. In nickel steel, however, the effect is somewhat different. The Ac. 1 point is quite uniformly raised but, according to available data, the Ac. 3 point, when the carbon is below 0.30 per cent, seems to be actually lower than in a steel of equivalent nickel content, while, with higher carbon, the Ac. 3 point is higher than in an equivalent nickel steel.

The presence of both nickel and chromium ensures considerable hardening with a rate of cooling through the critical range slower than that permissible in the case of steels with a similar content of either element. This makes the nickel-chromium steels especially suited for large sections requiring heat-treatment, giving them deep and uniform hardening power.

The low chromium content steels, namely, from 0.5 to 2.5 per cent chromium and low carbon content, are harder than the plain carbon steels of similar carbon content.

When chromium is present in carbon steels (0.15 to 0.40 per cent C) in higher proportions, namely, 12 to 20 per cent, an important series of "*stainless*" steels results; some of these special steels, however, contain other elements, including nickel and molybdenum.

Silicon. When present in certain proportions this element increases the strength and hardness of the steel, but reduces its ductility. A steel with 0.35 per cent carbon and 1.0 to 1.5 per cent silicon is practically free from large ferrite crystals and will be much stronger than the same carbon steel without silicon. For structural steels the silicon content usually lies between 0.9 and 1.5 per cent, and the

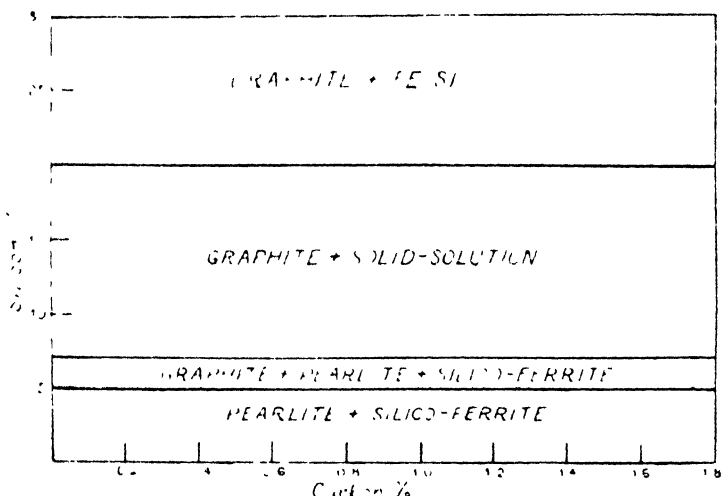


FIG. 98. STRUCTURAL DIAGRAM FOR SILICON STEEL. (GUILLET)

resulting steel has practically the same strength and ductility as low-nickel steel; it is cheaper to manufacture than the latter steel and is therefore widely used for structures such as bridges.

High-silicon steels (1.5 to 2.5 per cent Si) with 0.6 to 0.9 per cent of manganese and medium carbon content (0.4 to 0.5 per cent) are extensively employed for automobile, railroad, and general engineering purpose springs, since they combine—in the heat-treated condition—high tensile strength with high impact value and good ductility. Silicon is also employed in combination with other elements, such as chromium (known as *silico-chrom* steel) and vanadium for high strength spring materials.

When about 2.0 to 4.0 per cent of silicon is added to iron or low-carbon steel the resulting metal possesses important electrical properties, namely, a high permeability, low hysteresis and eddy current losses, being superior to pure iron. The silicon precipitates the carbon from solid solution and itself enters the steel in solid solution, possibly

as a FeSi compound. In this way the carbon in solution, which has the effect of reducing the permeability, is replaced by silicon compound having just the opposite tendency.

The silicon steels, which owe their development to Sir Robert Hadfield,* are much used for electrical stampings for the cores of transformers, for instrument diaphragms and other parts requiring

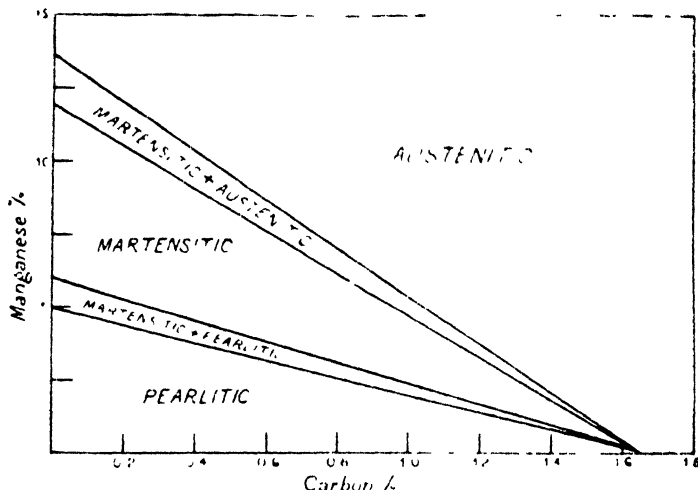


FIG. 99. STRUCTURAL DIAGRAM FOR MANGANESE STEELS. (GILLET)

excellent magnetic permeability and low hysteresis properties. A typical steel of this class is that known as "Stalloy," containing from 3 to 4 per cent silicon.

Steels containing 14 to 15 per cent of silicon combine high resistance to corrosion by commercial acids with good mechanical properties which enable them to be used for vessels, pipes, and other parts used in the handling of acids and other chemicals. Alloys containing about 20 per cent of silicon are even more resistant to corrosion, but are rather brittle and can be used only in the form of castings.

Manganese. Although present in limited proportions in practically all carbon and alloy steels, manganese, if used in higher proportions, imparts special properties to steels of certain carbon content and produces the *medium-manganese* steels and, in even higher proportions, the *high-manganese* steels which possess marked hardness and wear-resisting properties.

* "The Development of Alloy Steels," Sir R. Hadfield, F.R.S. (*Report of Empire Mining and Metallurgical Congress*, Sect. C, June, 1924).

When manganese is added to iron it lowers the melting-point progressively with increasing proportion of manganese from 1535° C. (pure iron) down to 1260° C. (pure manganese). Besides increasing the fusibility of steels it also lowers the critical temperatures or inversion points. In comparison with nickel only one-half the amount of manganese is required to produce a given depression of the critical temperature, thus about 14 per cent of manganese as compared with about 29 per cent of nickel is needed to preserve iron in the gamma condition. The transformation to martensite can be obtained with 6 to 7 per cent of manganese as compared with 13 to 14 per cent of nickel.

In the case of manganese steels* containing from 11 to 14 per cent, these are practically non-magnetic, and when quenched from high temperatures, namely, 950 C. to 1100 C., have purely austenitic structures, the carbon being in solid solution. An important feature of these steels is that the rate of heating and rate of cooling, as well as the maximum temperature before cooling, may all be varied within wide limits without the appearance of critical points or other changes in the general shapes of the heating and cooling curves. Quenching and annealing such steels produce effects opposite to those obtained in most other carbon and alloy steels.

The medium-manganese steels (up to about 1·8 per cent Mn) are stronger than carbon steels of similar carbon content, but the full strength properties are only developed by heat-treatment of moderately light sections.

Steels of this class having a low carbon content are used for case-hardening purposes, as they give a tougher core than plain carbon steels. With a carbon content of 0·30 to 0·60 per cent a wide range of engineering steels is produced. These include the 0·30 per cent carbon steels employed for machine steel parts which require appropriate heat-treatment in order to develop their full strength and hardness properties; and the 0·50 to 0·60 per cent carbon steels employed for oil-hardened gears, shafts, grinding balls, etc.

Vanadium. This element has a melting-point of 1720° C. and oxidizes slowly in air and more rapidly when heated. It is therefore a powerful deoxidizer when added to molten steel, but if more than about 0·25 per cent vanadium is left in the latter it tends to become brittle; it tends to inhibit the grain growth of steel above about 730° C.

A portion of the vanadium appears† to go into solid solution under normal conditions in the ferrite portion of the steel—the ferrite of

* Discovered by Sir Robert Hadfield in 1882.

† "Influence of Vanadium on Steels," A. McWilliam and E. T. Barnes (*Journ. Iron and Steel Inst.*, 1911).

vanadium steel is much more resistant to wear and to the formation of slip bands than ordinary ferrite. Also, as it tends to oppose the ready passage of carbides through the metal, its effect is to produce a steel of marked sorbitic structure. Further, the strengthening seems to be due to the formation of complex carbides, especially susceptible to improvement by tempering.

It is believed that only a few hundredths of 1 per cent of the vanadium combines with the ferrite, but this very small amount appears to increase the strength, toughness, and hardness of the ferrite. Nearly all the vanadium, however, is found in the pearlite, in chemical combination with the cementite, as a compound carbide of vanadium and iron in the case of ternary steels, and as more complex carbides in the case of quaternary steels.

The effect of vanadium on the physical or mechanical properties of steel increases with the percentage of vanadium up to about 1 per cent, after which there is a decrease. With over 3 per cent of vanadium steel is actually softened, even after quenching.

An important use of vanadium is in combination with chromium to form the well-known chrome-vanadium steels of industry, the resulting steels when suitably heat-treated are extremely tough and strong. The low-carbon steels are employed for case-hardening purposes and the medium-carbon ones for oil-hardening axles, gears, crankshafts and similarly highly stressed parts for automobile, aircraft, and general mechanical engineering purposes.

Chrome-vanadium steels of about 1.0 per cent Cr and 0.15 per cent V are used for automobile springs, both flat and coiled.

Vanadium is also used to produce a high degree of hardness in high-speed tool steel, armour-piercing projectiles, magnets, gun-shields, torpedo tubes, rock-drills, etc.

Vanadium steel castings are noted for their high elastic properties, strength, and toughness and are employed for such purposes as draw-bars, cross-heads and frame parts of locomotives.

Vanadium steel castings have good impact strength qualities and respond readily to simple heat-treatment. The plain *carbon-vanadium* and the *chrome-vanadium* steels are widely used for such castings. *Nickel-vanadium* steel castings containing about 1.5 per cent nickel and from 0.2 to 0.3 per cent carbon have excellent strength and ductility properties. Thus, the tensile strengths range from 37 to 44 tons per sq. in., with 29 to 27 per cent elongation on 2 in. and 59 to 54 per cent reduction of area. The Izod impact values lie between 60 and 48 ft.-lb.

Nickel-vanadium steel castings are now finding favour in railway service, steel-making plant, and other industrial equipment where

resistance to wear and tear, resistance to shock, and breakdown through vibration have to be guarded against.

The manganese-vanadium type of steel casting also shows great promise. Pearlitic manganese steel castings within the past few years have attained considerable industrial prominence, but their application is apparently possible only within limits.

A well-known *carbon-vanadium steel* used for castings contains C, 0.35; Mn, 0.90; Si, 0.40; and V, 0.18 (percentages). It has a yield point of 22.5 tons per sq. in. and tensile strength of 38 tons per sq. in., with 22 per cent elongation on 2 in. and 45 per cent reduction of area. By double normalizing and tempering treatment the yield point and tensile strength can be increased to 25 and 41 tons per sq. in. respectively, with 25 per cent elongation, 47 per cent reduction in area, and Izod impact value of 31 ft.-lb.

In most of the vanadium steels mentioned the vanadium content seldom exceeds 0.25 per cent. In chrome-vanadium steels the proportion of chromium is from 4 to 6 times that of the vanadium.

Molybdenum. This element exercises an important influence in improving the mechanical properties of steel both at normal and elevated temperatures. In addition it reduces appreciably the tendency of the steel to "temper brittleness" and thus tends to remove many difficulties associated with the fabrication of temper brittle steels—a property often associated with alloy steels. It also permits the use of higher tempering temperatures after quenching, viz. 100° to 200° C° higher than for similar composition steels without molybdenum.

Molybdenum also reduces the effect of mass. It acts by promoting depth hardening, and even in small percentages—as low as 0.1 per cent—it diminishes the mass effect: up to about 0.6 per cent it gives practically uniform depth hardening on masses up to 8 in. diameter. Tests made at Woolwich Arsenal on heavy hollow forgings of nickel steel and nickel-chromium-molybdenum steel showed* that the latter steel of a section of 4½ in. varied only by 6 Brinell numbers from inner to outer surface and a section of 11½ in. by only 10 Brinell numbers. For the alternative nickel steel the corresponding variations were 15 Brinell numbers for a section of 3½ in. and 51 for one of 7½ in.

It was concluded that (1) the property of reducing mass effect renders the use of molybdenum more justifiable in the case of nickel-chromium steels than in most other alloy steels, (2) direct use can be made of the results of treatment on a small scale in order to forecast properties of large forgings after heat-treatment.

* "Influence of Molybdenum on Medium-carbon Steels containing Nickel and Chromium," Research Dept., Woolwich R.D. Report No. 67.

When molybdenum is added to steel in proportions up to about 1 per cent, it does not exert any deoxidizing influence, but its value depends on the molybdenum being retained in the steel as an alloy. The molybdenum dissolves in the ferrite and combines with the carbon in the steel, forming fine-grained strong carbides which are retained in the solid solution in cooling through the critical ranges. Heat-treated molybdenum steels are characterized by their very fine grain structure. When added to straight carbon steels, molybdenum improves their physical qualities, but its most marked influence is experienced when it is used in combination with one or more of the other alloying elements, e.g. nickel, chromium, vanadium, etc. The intense activity of molybdenum as an alloying constituent of steel is shown by the fact that the maximum quantity added to steel, other than high-speed tool steel, is 1 per cent for most purposes, however, one-half of this quantity is usually sufficient.

The general manner in which the addition of molybdenum (0.24 to 0.81 per cent) improves the mechanical properties of plain carbon and alloy steels is shown in Fig. 100,* in which the properties of the steels of the stated compositions above, without molybdenum, are shown on the left-hand side, whilst those of the same steel, but with the stated addition of molybdenum, are shown on the right-hand side. The results show the invariable increase in the yield point and tensile strength due to the presence of molybdenum. The steels in question were heat-treated and tempered to give the best results in each case.

Since the nickel-chromium-molybdenum steel is of special importance in its engineering applications, it is of interest to compare the properties of two similar steels, one with, and the other without, molybdenum. The following are the percentage compositions of two typical steels—

	C	Si	Mn	P	S	Ni	Cr	Mo
Nickel-chromium steel	0.29	0.18	0.53	0.035	0.037	3.68	0.81	Nil
Nickel-chromium-molybdenum steel	0.27	0.16	0.59	0.034	0.038	2.60	0.63	0.60

The nickel-chromium steel was oil-hardened at 900 °C and tempered at 600 °C, by quenching in water.

* "Molybdenum in Steel and Iron," Publication of High Speed Steel Alloys Ltd., Widnes.

Tensile Strength (TS) and Yield Point (YP) in Tons per Sq Inch
Reduction of Area (RA) and Elongation (EL) in 2 in Percent

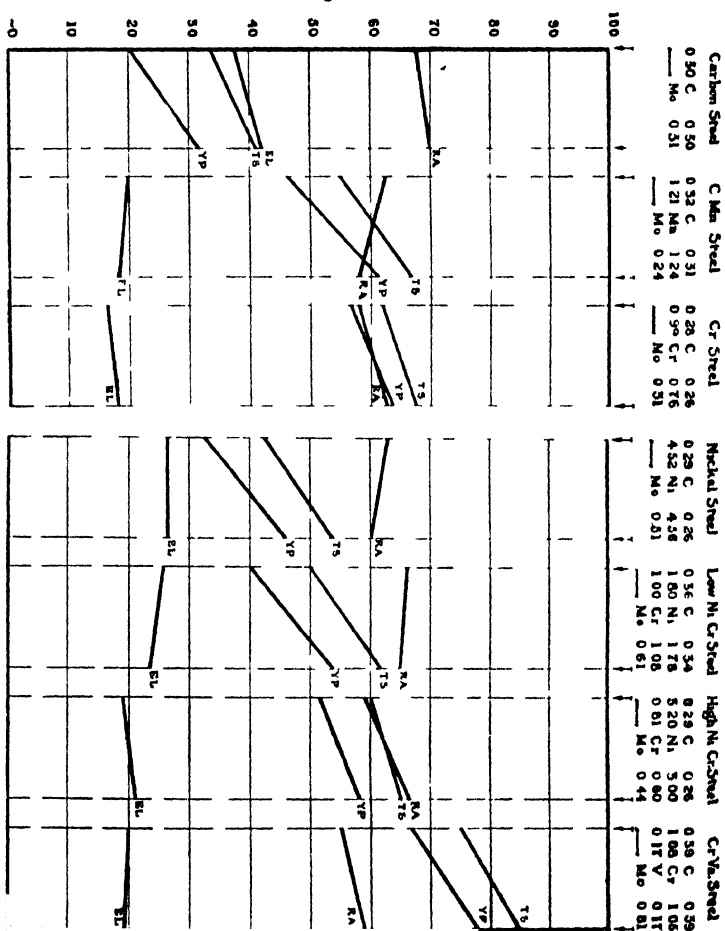


FIG. 100 ILLUSTRATING EFFECT OF COMBINATION OF MECHANICAL PROPERTIES OF PLAIN AND ALLOY STEELS

The nickel-chromium-molybdenum steel was oil-hardened at 900° C. and tempered at 650° C. by cooling in the furnace.

The results of tensile tests made on specimens of 0.564 in. diameter made from 1-in. diameter bars are shown in Fig. 101. The following values give the full results of these tests in tabular form.

TABLE 48
MECHANICAL TEST RESULTS

	Elastic Limit Tons per sq. in.	Yield Point Tons per sq. in.	Tensile Strength Tons per sq. in.	Elongation in 2 in. per cent.	Reduction of Area per cent.	Brinell Hardness	Impact ft.-lb.
Ni-Cr steel	36.0	44.0	50.9	23	64	242	51
Ni-Cr-Mo steel	44.0	50.0	56.5	24	67	271	58

In general it has been found that the effect of molybdenum as an alloy in steel (1) at equal ductility gives an increase in the elastic limit, yield point, tensile strength, and impact value, and (2) at equal elastic limit gives an increase in ductility and a marked increase in impact value.

There is a fairly wide range of molybdenum steels, each type having its own special applications. The more important steels include carbon-molybdenum, copper-molybdenum, chromium-molybdenum, manganese-molybdenum, nickel-molybdenum, and nickel-chromium-molybdenum. Reference is made to some of these steels later in this chapter.

Tungsten. This element is used in certain classes of tool, valve, and magnet steel. Its inclusion in the composition of alloy tool steels of the high-speed type in which the hardness is retained at elevated cutting temperatures is due to its effect in lowering the transformation temperature sufficiently for the steel to become "self-hardening," i.e. the steel will give the required hardness after heating to redness - or the appropriate hardening temperature - when cooled in the air.

The original tungsten or "Mushet" tool steel contained about 6.6 per cent of tungsten, but improved tool steels have from 15 to 20 per cent of this element.

Steels containing from 5 to 6 per cent of tungsten possess good magnetic qualities and have been employed for the magnets of magnetos, electrical instruments, small generators, etc. Newer alloy

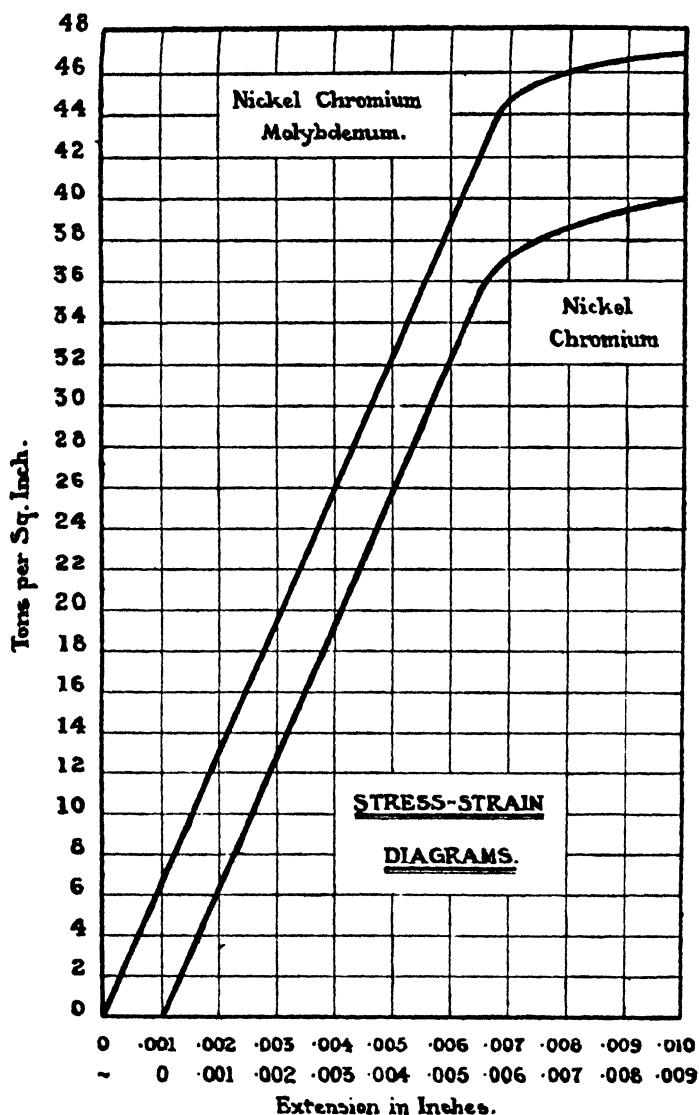


FIG. 101. EFFECT OF MOLYBDENUM ON MECHANICAL PROPERTIES OF NICKEL-CHROMIUM STEEL.

steels containing chromium, cobalt, nickel, and aluminum have now, to a large extent, replaced the original tungsten magnet steels in all cases where the maximum magnetic properties i.e. coercive force and remanence, are required—such steels are greatly superior to tungsten steel.

Copper. This improves the mechanical properties of cast steel when

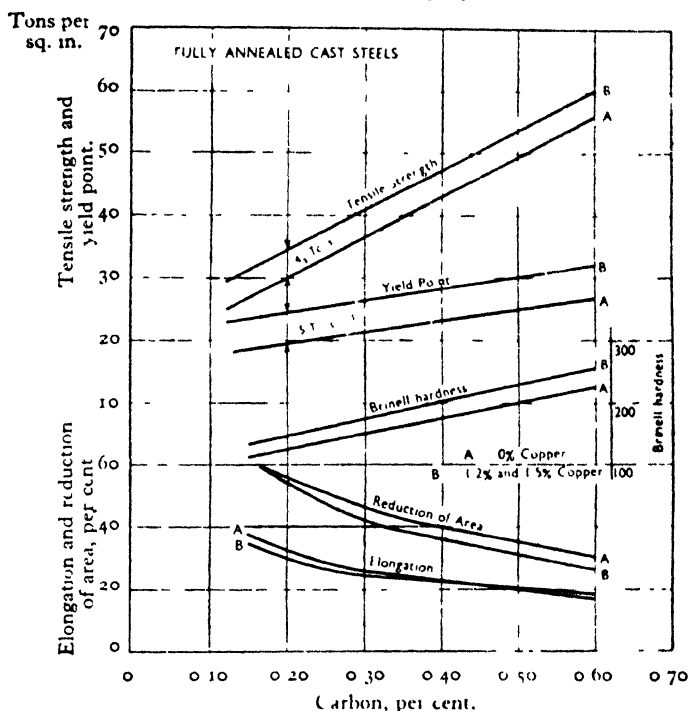


FIG. 102. MECHANICAL PROPERTIES OF FULLY ANNEALED CAST STEELS HEAT TREATED AT 900° C. (1650° F.) FOR 5 HOURS, AIR COOLED, REHEATED TO 855° C. (1575° F.) FOR 1 HOUR, AND FURNACE COOLED (LONG).

1 to 3 per cent is used—both the yield point and tensile strength are increased, independently of the carbon content of the steel. It reduces the tendency to corrosion and gives grain refinement. Fig. 102* shows the effect of copper, up to 1.5 per cent, upon the mechanical properties of normalized cast steels of different carbon contents up to 0.60 per cent. Up to about 0.5 per cent copper the improvement in the mechanical properties is small, but above this percentage the tensile strength

* *Copper in Cast Steel and Iron*, Copper Development Association, London.

increases rapidly. Thus, in a 0.3 per cent carbon cast steel 2.4 per cent addition of copper will raise the tensile strength or yield point by as much as 16 tons per sq. in. At ordinary temperatures the ferrite is saturated with copper at 0.35 per cent and the increase in strength appears to be due to the strain on the ferrite lattice imposed by the supersaturated copper. The limit of supersaturation occurs at about 1 per cent copper in a normalized steel casting. Additions of more than 3.5 per cent copper will not influence the strength of cast steel owing to the fact that the limit of solubility of copper in austenite at the normalizing temperature is reached and secondary copper appears.

Copper lowers the ductility and impact resistance of cast steel, but for a given increase in tensile strength the loss of ductility and impact resistance is less if copper is added than if the carbon content is increased. That is to say, for a given tensile strength a copper steel is tougher and more ductile than a plain carbon steel.

Copper steels are susceptible to low-temperature "ageing" or precipitation-hardening treatment which produces substantial increases in tensile properties, particularly of low-carbon steels.

The improvement in mechanical properties arising from copper additions to cast steels containing other alloying elements is in general of the same order as those obtainable in plain carbon steels. Copper is very effective when used in conjunction with the cheaper alloys such as manganese, chromium, and silicon. For example, a tensile strength of over 60 tons per sq. in. is obtainable in a 0.3 per cent carbon steel containing 1.25 per cent manganese and 2 per cent copper after normalizing and ageing.

Copper additions increase the fluidity of cast steels, and up to 3.5 per cent may be added to facilitate running intricate castings.

Copper is added to high-carbon steels used for automobile crankshafts, etc., to accelerate annealing, to improve tensile and fatigue properties, and to promote fluidity.

Copper increases the corrosion resistance of cast steel; for this reason structural steels used for buildings, bridges, etc., are frequently of the copper-content class.

Other Alloying Elements

Other elements which impart special properties to steels include cobalt, boron, aluminum, lead, titanium, etc.

Cobalt is used in conjunction with other alloying elements, notably tungsten, molybdenum, chromium, and vanadium, in percentages of 3 to 5, for high-speed tool steels. It also imparts excellent magnetic properties to iron. Thus, the addition of about 35 per cent of cobalt

increases the coercive force and remanence by about 15 per cent. The addition, in suitable proportions, of hardening elements such as chromium and tungsten results in an excellent magnet steel of superior magnetic properties to tungsten steel. Cobalt also forms the principal constituent of the high-speed tool-cutting alloy known as *Stellite*, in which the iron content is very low, namely, about 3 to 4 per cent.

Boron, when present in amounts up to about 0.8 per cent, imparts hardness to steel and gives improved plasticity well below the solidifying temperature of ordinary steel.

Aluminium is a constituent of certain intruding steels and also of one of the best magnet steels hitherto discovered, namely, that due to Mishima of Japan, who found that an alloy of about two parts of iron to one of nickel and one of aluminium gave superior magnetic qualities to those of any previously known alloy.

Lead. This element does not alloy with iron but occurs scattered throughout the matrix in finely divided particles of metallic lead, often of the cubical pattern. The presence of 0.2 to 0.25 per cent of lead gives marked improvement to the machining properties of steel. A typical steel of this class is "Ledloy." Some interesting data on the improved machinability of these steels were given in *Automotive Industries*,* which mentions the case of a small plunger, when made in S.A.E. 1115 steel (a free-cutting plain carbon steel with 0.10 to 0.20 C), this required 11 secs. to machine.

When lead was introduced into this same steel the time required was reduced to $3\frac{1}{2}$ seconds. This was cold drawn steel with a turning and cut-off operation on a six-spindle automatic. On fulcrum shafts of S.A.E. 1020 (a plain carbon steel with 0.15 to 0.25 C), which is always a bad machining steel on automatics, the addition of lead proved to be beneficial. On several jobs the surface speed was increased from 75 to 125 surface ft. per min.

Lead has one advantage in that it does not seem to impart any unfavourable properties to steel. The leaded steel can be readily rolled and forged, and it carburizes and hardens satisfactorily.

Thus the results of an investigation made by the American originators of "Ledloy" lead-bearing steel† show that the lead is almost completely without effect on the mechanical properties at room temperature of carbon steels containing 0.15 to 0.5 per cent of carbon in the normalized, cold-drawn, and oil-hardened and tempered conditions. It has very little effect on the impact figure at raised temperatures. It is also without appreciable influence on depth of carburizing

* 15th July, 1939.

† *The Metallurgist*, 25th August, 1939.

and on hardenability, but the lead-bearing steels have a slightly finer grain size and perhaps for this reason show slightly less depth hardening.

In commercial lead-bearing steels, containing under 0.25 per cent of lead, no globules are visible under the microscope. The effect of lead on machining is additive to that of sulphur, but the properties of the high-sulphur, free-cutting steels are not affected in other respects by lead. In such steels some of the lead is contained in the inclusions, as is shown by heating a polished section to 480° C., after which lead globules are visible in the sulphide.

An interesting fact concerning lead steels is that the chips resulting from machining are at a *lower temperature* than those from lead-free steels machined under the same conditions: the former show a yellow temper colour and the latter are blue. This has been explained by the nature of the lubrication produced by sub-microscopic particles of lead.

Nickel Steels

Nickel steels are widely used in engineering work for stressed members, where ordinary carbon steels would be unsuitable or too heavy. The nickel steels in general use include: (1) The low-carbon, case-hardening steels; (2) the plain nickel steels containing from 0.3 to 0.45 per cent carbon, with nickel up to 5 per cent, and (3) the high-nickel steels with a nickel content of 25 to 38 per cent.

Case-hardening Nickel Steels

These steels are employed in place of plain carbon case-hardening steels for more heavily stressed parts requiring a very hard case and a tougher core of much higher tensile strength.

The most widely used nickel steels of this group are those with 0.10 to 0.15 per cent carbon and 3.0 and 5.0 per cent nickel respectively. The 3 per cent steel gives a tensile strength, in the carburized and subsequent heat-treated condition, of 45 to 60 tons per sq. in., and the 5 per cent steel from 55 to 65 tons per sq. in.

The strength properties of the core are improved by the addition of about 0.3 per cent of chromium: molybdenum is also used for the highest grades.

The mechanical properties of a plain carbon case-hardening steel, a 3 per cent nickel, and a 5 per cent nickel case-hardening steel, employed commercially, are given in Table 49.* The compositions and heat-treatments of these steels are also shown. The results emphasize the beneficial effect of the nickel upon the yield point and tensile strength, and also show the reduced ductility as compared with the carbon steel.

* Thos. Firth & John Brown Ltd.

TABLE 49

NICKEL-BASE HARDENING STEELS

Description	Composition, per cent				Typical Mechanical Properties on 1-in. Bar					
	C	Si	Mn	N	Heat treatment	Max. Stress, ksi	Yield Point, ksi	Elongation, per cent	Red. of Area, per cent	Tensile Strength, ft. lb.
Carbon steel	0.12	0.2	0.65		W Q 300	W Q 760	36	30	60	50
3 per cent nickel steel	0.12	0.2	0.40	3.0	W Q 800	W Q 760	40	32	22	50
5 per cent nickel steel	0.10	0.2	0.30	0	W Q 830	W Q 760	42	40	18	55

W Q water quenched

O Q oil quenched

TABLE 50
NICKEL-CHROMIUM CASE-HARDENING STEELS

Description	Composition (per centage)					Mechanical Tests on 1½ in Bar				
	C	Si	Mn	Ni	Cr	Heat treatment	Max Stress per sq in	Elonga- tion per cent	Red of Area per cent	Izod ft lb
3 per cent nickel steel	0.12	0.25	0.40	3.00	0.30	O Q 860 W Q 770 C	45 60	18*	45*	40*
5 per cent nickel steel	0.14	0.25	0.40	5.00	0.30	O Q 850 W Q 770 C	67*	13*		30*
3.5 per cent nickel steel	0.12	0.25	0.40	3.50	0.80	O Q 850 W Q 760 C	60	22	55	50
4.25 per cent nickel steel	0.14	0.25	0.40	4.25	1.25	O Q 830 W Q 760 C	85	14	38	35

* Maximum values

TABLE 51
MEDIUM TENSILE STRENGTH NICKEL STEELS

Description	Composition (percentage)					Typical Mechanical Properties on 1½ in Bar					
	C	Si	Mn	Ni	Cr	Heat treatment	Max Stress Tons per sq in	Yield Point Tons per sq in	Elonga- tion per cent	Red. of Area per cent	Izod ft.-lb.
1 per cent nickel steel	0.35 to 0.45	0.30*	1.20*	1.0	—	O H 850 I 500 650 C	40 50		22†	40†	35
3 per cent nickel steel	0.30	0.25	0.65	3.0	—	O H 850 T 580 650 C	50	38	25	60	50
3½ per cent nickel steel	0.40	0.25	0.65	3.5	0.25	O H 830 T 530 650 C	60	46	21	57	45
5 per cent nickel steel	0.20	0.25	0.50	5.0	—	O H 830 T 500 600 C	52	40	20	54	45

In each case, after the carburizing operation, the part was heated above the critical point and quenched in oil or water and then hardened by reheating to the lower temperature (760 °C) and quenching in oil or water. Typical applications of the 3 per cent nickel case-hardening steels include their use for more heavily stressed parts than those for which plain low-carbon steels are suitable, in aircraft, automobile, and general engineering work. The 5 per cent nickel steels are employed for parts requiring rather higher core strengths, typical instances being aircraft and automobile gudgeon pins, camshafts, crankshafts, connecting rods, overhead valve gear, timing wheels, automobile steering gear worms and quadrants, and high-strength forgings for general engineering purposes.

Nickel Case-hardening Steels with Chromium Content

The effect of the addition of chromium up to about 1.3 per cent of chromium is to improve the core strength well above that obtainable from plain nickel steels without affecting materially the ductility or Izod impact value.

The results given in Table 50 (p. 212) are typical of such case-hardening steels, and refer to the steel heat-treated as shown in the table.

Medium-tensile Nickel Steels

This group of alloy steels has a wide application in engineering work for components requiring greater strength and toughness for their weight than the equivalent plain carbon steels. In most instances the carbon content is kept low, namely, between about 0.35 and 0.45, whilst the nickel content, according to the purpose for which the steel is needed, ranges from about 1 to 5 per cent, usually with chromium. These steels give tensile strengths in the heat-treated condition between 40 and 60 tons per sq. in.

Table 51 (p. 212) gives the compositions, heat-treatments, and mechanical properties of typical commercial steels.*

In general the *forging of these steels* should be carried out within a limited range of temperatures: as a rough guide it may be stated that the temperature should not exceed 1150 °C, nor fall below a cherry-red heat. The steel must be heated gradually and allowed to soak at the forging temperature. The *hardening* is carried out by heating to the temperatures indicated in the preceding table and quenching in oil. Tempering then follows this operation.

* *Mechanical Properties of Nickel Alloy Steels*, Mond Nickel Co. and Thos. Firth & John Brown Ltd.

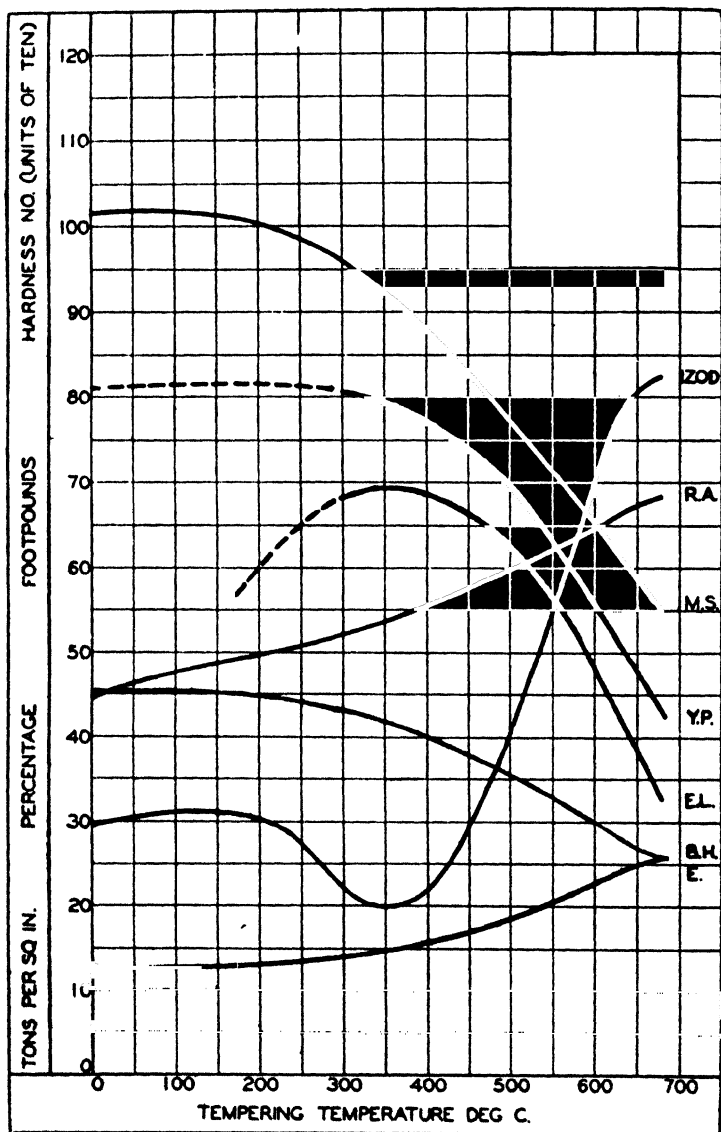


FIG. 103. MECHANICAL PROPERTIES OF 3 PER CENT NICKEL STEEL
TEMPERING CURVES AFTER OIL QUENCHING
1½ in. diameter bars quenched in oil from 850° C.

The effect upon the mechanical properties of tempering a nickel steel with chromium and molybdenum content is illustrated in Fig. 103. It will be observed that the maximum stress (M.S.), yield point (Y.P.), elastic limit (E.L.), and Brinell hardness (B.H.) all diminish in value as the tempering temperature is increased, whilst the reduction of area (R.A.) and Izod impact value (Izod) both increase as the temperature is increased. It should be pointed out that if the steel is reheated to any given tempering temperature and quenched in oil, it will have the mechanical properties shown by the graphs in Fig. 103.

The initial hardening temperature of this steel is 850 C., oil quenching being used; the results refer to $1\frac{1}{2}$ in. diameter bars.

Machining of these nickel steels can usually be undertaken with the steels in the oil-hardened and well-tempered condition. In the case of large forgings, where the steels may be too hard for subsequent machining after heat-treatment, they should be partly softened by heating to 630 to 650 C. and cooled slowly in air or in the furnace. It is usual for the steel manufacturers to supply nickel steel bars in the heat-treated condition ready for machining.

Applications of Nickel Steels

The steels containing up to about 3 per cent of nickel are widely employed for forged and "turned from the rod" parts for automobile crankshafts, connecting rods, front axles, stub axles, steering gear parts, aircraft engine cylinders, spindles, gear-box shafts, torque tubes, chassis frames, and for the shafts, axles, and spindles of high-class machinery.

The 3.5 per cent nickel steel shown in Table 51 was developed for aircraft engine bevel gear shafts, hand-starter shafts, airscrew bolts, connecting-rod bolts, and similar high-tensile parts.

The 5 per cent nickel steel, which is not quite so strong as the lower nickel steels given in Table 51, is employed for plate fittings in aircraft, for turbine blading and shrouding strip.

High-nickel Steels

These steels or ferro-nickel alloys have a carbon content of about 0.3 to 0.5 per cent and, according to their compositions, are employed on account of their resistance to corrosion, low thermal expansion, or electrical properties.

They are austenitic and not subject to heat-treatment, but are, however, quite tough and strong, while some have a low thermal expansivity and are very resistant to corrosion in air, fresh or sea

water. These steels are used for gas engine valves, boiler tubes for water or fire, and valve stems in salt water lines. The alloys may be forged or rolled, but are not so readily machined as ordinary steel. They may have the following average tensile properties in the natural state without heat-treatment.

TABLE 52
HIGH-NICKEL STEELS

Tensile Strength Properties	Class of Nickel Steel		
	25 to 28 per cent Ni	30 to 35 per cent Ni	35 to 38 per cent Ni
Tensile strength, tons per sq. in.	38-41	38-42	45-51
Yield point, tons per sq. in.	15.5-22	18-22	28-35
Elongation on 2 in., per cent	30-35	30-40	25-35
Reduction of area, per cent	50-60	40-60	50

The ferro-nickel alloys having from 20 to 30 per cent nickel can be obtained in the *non-magnetic condition* by cooling at normal rates from rolling and forging temperatures, such alloys are employed for non-magnetic components requiring strength and toughness.

Low-expansion Nickel-iron Alloys

As the nickel content is increased from 28 to 35 per cent, the thermal expansion coefficient at normal air temperatures diminishes rapidly, but beyond about 36 per cent it increases rapidly. Thus for nickel contents of 28, 30.4, 34.6, 35.5, 37.3, 39.4, and 44.4 per cent, the corresponding coefficients of linear expansion per deg. C. are, respectively, 1131×10^{-6} , 458×10^{-6} , 137×10^{-6} , 87×10^{-6} , 537×10^{-6} , and 856×10^{-6} . The lowest coefficient is that corresponding to 35.5 per cent nickel.

It may be of interest for comparison purposes to give the values of the coefficients for mild and hard steels, these are 1078×10^{-6} and 1240×10^{-6} respectively. It may also be mentioned that a ferro-nickel alloy having 47.5 per cent of nickel gives the *same thermal expansion coefficient as glass* and platinum, so that wires of such an alloy fused into glass give satisfactory results over a wide temperature range.

Special low-expansion nickel-iron alloys which have found important commercial applications include Invar, Elinvar, Dilver, and Platinite.

Invar contains 35.5 per cent of nickel, 0.18 per cent carbon, and

0.42 per cent manganese. It has an expansion coefficient of 87.7×10^{-6} per deg. C. The mean value for the expansion coefficient α between 0 and t C. is given by

$$\alpha = (0.877 + 0.00117t) \times 10^{-6} \text{ per deg. C.}$$

The range covered by t should not exceed 200 C.

Invar has about one-twelfth the expansion per deg. C. of iron and one-seventeenth that of brass. It melts at 1425 C., has a specific gravity of about 8 and electrical resistivity of 85 microhm cm. This alloy is much used for the pendulum rods of clocks, for standard length measures, steel tapes for accurate measurements, balance wheels of watches, etc. It is very resistant to corrosion in water. Invar is also used in the construction of a certain type of *aluminum alloy piston* known as the *Invar Strut* one—in order to reduce the overall coefficient of expansion in the radial direction to that of the cast iron cylinder. Such pistons can be made with lower cylinder clearances than ordinary aluminum alloys, and are therefore immune from the cold knocking effect, known as *piston slap*.

Elinvar, one of the modern nickel-iron alloys, consists of 35 per cent nickel to which about 12 per cent chromium, or its equivalent, with small quantities of manganese, tungsten, or carbon are used in conjunction with chromium additions—the rest is iron.

This alloy possesses a *very low coefficient of linear expansion*—namely, about 120×10^{-6} per deg. at 20 C.—and a practically *invariable modulus of elasticity*. The development of this alloy in connection with single metal balances for high-grade watches has enabled a less expensive method of compensation to be obtained.

Dilver has a coefficient of thermal expansion very nearly the same as that of ordinary glass.

Platinite is a 46 per cent nickel-iron alloy, with a thermal expansion equal to that of platinum (900×10^{-6}). It has been used in place of platinum for sealing in the leads of electric light bulbs. It has now been superseded by a compound wire having 38 per cent nickel-steel core encased in copper; this wire is sometimes platinized externally.

Nickel-iron Electrical Alloys

Various alloys containing iron and nickel are used in electrical work in connection with such applications as high resistances, non-magnetic parts, electromagnets, etc. Since these alloys are more appropriately associated with those of nickel, they are dealt with in the section on Electrical Steels and Iron Alloys (Chapter VIII).

AMF Low-temperature High-strength Alloy

This is a nickel-iron alloy having an expansion coefficient similar to that of steel, but, unlike the latter, it possesses great strength ductility, and resistance to shock at very low temperatures. It has the following percentage composition, namely, C, 0.2 to 0.4; Ni, 55 to 60; and Mn, 0.33.

At the temperature of liquid air it has the following mechanical properties -

Tensile strength	51 tons per sq. in.
Elastic limit	25 " "
Elongation	40 per cent
Reduction of area	55 " "

It is therefore suitable for components employed in liquid air and refrigerator plant, such as valves, shafts, etc.

Non-magnetic High-expansion Steel

A special nickel-chromium-manganese steel, known as Firth N.M.C., has been produced for parts which have to be used in conjunction with non-ferrous alloys, such as those of aluminium, with high coefficients of thermal expansion. The steel in question has a thermal expansion coefficient of 2100×10^{-6} which is only slightly lower than that of aluminium, so that it can be used for steel liners in aluminium aircraft engine cylinders, piston skirts, engine bearers, etc.

It is non-magnetic and has a high yield point, namely, 30 to 50 tons per sq. in. It is used in electrical work for alternator rotor caps and wedges, coil-binding rings, distance pieces, non-magnetic binding wire and strip, etc.

Nickel-chromium Steels

These alloy steels include the case-hardening low carbon and the oil- and air-hardening grades containing from 0.5 to 2.0 per cent chromium and 2.0 to 5.0 per cent nickel, giving a range of tensile strengths from about 55 to 125 tons per sq. in., according to composition and heat-treatment, such steels come within the range of medium to high-tensile ones, and are stronger, harder, and tougher than the plain nickel steels.

The carbon content lies between about 0.3 and 0.4 per cent, as a general rule. Table 53 gives the compositions and test properties of some typical commercial nickel-chromium steels.

Most of these steels conform to B.S.I. or D.T.D. specifications.

The medium-tensile strength steels are forged between temperatures of 1150° C. and that corresponding to a cherry-red heat. They require

TABLE 53
COMPOSITIONS AND MECHANICAL PROPERTIES OF NICKEL-CHROMIUM STEELS

Description	Composition				Mechanical Properties on 14 in Bar				
	C	Mn	Ni	Cr	Heat treatment	Tensile strength, lb/in ²	Elongation, per cent	Reduction of Area, per cent	Izod, ft-lb
3 per cent nickel-chromium* Mild nickel-chromium†	0.50 0.18-0.25	0.60 0.20-0	0	2.5 0.4-0.5	Oil quench and temper	60 60,000	24 14	27 55	50 40
Medium nickel-chromium†	0.25-0.35, 0.25-0	0.25-0	0.3-0.5	0.8-1.0	Oil quench and temper	60 60,000	18 10	50 25	40 20
14 per cent nickel-chromium* 44 per cent nickel-chromium*	0.35 0.30	0	1.0 0.25	1.0 0.8-1.0	Oil quench and temper	60 60,000	18 10	25 25	8 10
Nickel-chromium gear steel†	0.25-0.32, 0.25-0	0.60	0.5-0.7	1.0-1.2	Oil quench and temper	60 60,000	18 10	25 25	8 10
Super air-hardening nickel-chromium†	0.25-0.30, 0.25-0	0.60	0.5-0.7	1.0-1.2	Oil quench and temper	60 60,000	18 10	25 25	8 10

* Jh = 1 ft-lb (1.36 in-lb) † High-strength steel (high ratio) Ltd

to be heated slowly, followed by a thorough soaking at the forging temperature: they should not be put into the already heated furnace.

— Machining can be done in the oil-hardened and well-tempered condition, using high-speed steel tools, except for large forgings, where an intermediate heat-treatment is advisable. —

The high-tensile steels are forged at 1100 °C. to a bright red heat, but care is necessary as some of these steels exhibit a tendency to air-harden, so that the forging should not be carried out below a light red

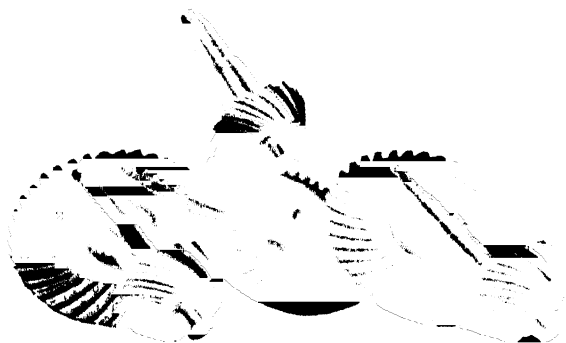


FIG. 106. TYPICAL BACK AXLE SPIRAL BEVEL GEARS IN 3.0-3.7 PER CENT NICKEL, 0.5-1.0 CHROMIUM, AND 0.25 PER CENT MOLYBDENUM CASE-HARDENING STEEL.
(D. BROWN, L.D.)

heat and the parts must be protected against draughts during cooling, in order to avoid distortion or internal cracking.

The *hardnesses* of the mild and medium nickel-chromium steels given in Table 53 are 228-277 and 255-293 Brinell respectively. The values for the nickel-chromium gear steel and the super air-hardening steel given in the same table are 444-555 Brinell in each case.

The *effect of heat-treatment* upon the mechanical properties of a high-tensile nickel-chromium steel is illustrated by the results shown in Fig. 106 for the S.A.E. No. 3340 steel, the percentage composition of which is as follows: C, 0.35 to 0.45; Mn, 0.30 to 0.60; P, 0.04 (max.); S, 0.04 (max.); Ni, 3.25 to 3.75; Cr, 1.25 to 1.75.

The steel was oil-quenched at 1400 to 1450 °F. (760 to 786 °C.) and tempered or drawn at the temperatures shown in Fig. 106. The Ac. 1 and Ac. 3-2 points for this steel are 1345 °F. (729 °C.) and 1345 °F. (729 °C.).

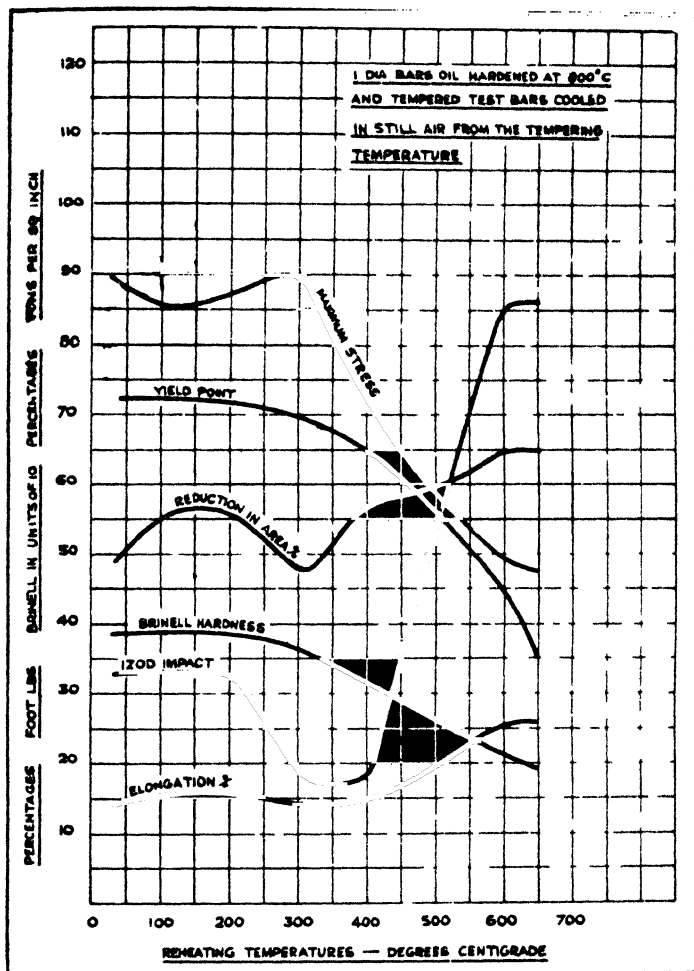
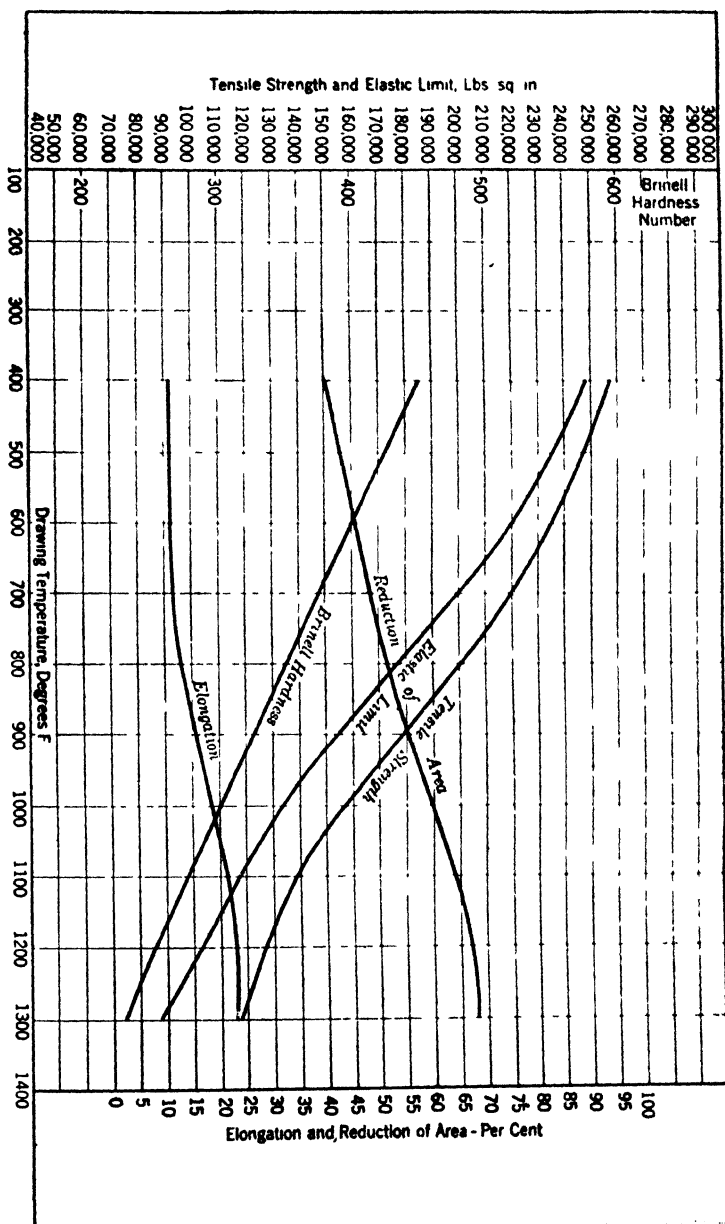


FIG. 10. PROPERTIES OF CAST HARDENING NICKEL CHROMIUM STEEL
(ARMSTRONG WHITEWORTH)

Fig. 106. MECHANICAL PROPERTIES OF SAE No. 3340 NORMALIZED STEEL



Applications of Nickel-chromium Steels

In general the medium tensile steels are employed for the more highly stressed parts in automobile aircraft and general engineering, where greater strength for weight combined with ductility and toughness than would be obtainable from plain carbon or nickel steels is desirable.

The high-tensile steels give the maximum tensile strengths and hardnesses and are employed for highest grade engineering parts requiring maximum strength to weight ratio, resistance to fatigue and hardness. Typical applications of the medium tensile steels include aircraft and automobile crankshafts and connecting rods, bolts for cylinders, connecting rods, cylinder heads and crankcases, gear box shafts, rear axles, machinery shafts and axles of high strength to weight, propellers and pressure vessels.

The high-tensile steels of 100-125 tons per sq. in. tensile strength are employed for aircraft and automobile gear wheels, e.g. cam gears, aircraft reduction gears, supercharger gears, highly stressed shafts, tubes, turnbuckles, etc.

65-ton Nickel-chromium steel. This steel is used for highly stressed aircraft engine connecting rods and parts performing similar duties. It has the following specification: * C 0.22 to 0.28, Si 0.30 (max.), Mn 0.35 to 0.65, P and S 0.05 (max.), Ni 2.75 to 3.50, Cr 1.0 to 1.40, Mo 0.25 (percentages), Vanadium (0.25) and tungsten (1.0) are mentioned as optional constituents. The mechanical properties of this steel when oil hardened at 830° C. and tempered are given in Fig. 107, where the same annotation is used as for Fig. 103 on page 214. The tensile strength as oil hardened is over 100 tons per sq. in., but at the recommended temper, corresponding to 600° to 500° C., it falls to 65 to 77 tons per sq. in. respectively, with a Brinell hardness of 350 to 300.

B.S.I. Specification for Nickel-chromium Steels

The British Standards Institution includes a number of nickel-chromium steels in its specifications for automobile steels. The following steels containing nickel and chromium are specified: (1) 3 per cent nickel steel (not more than 0.30 per cent chromium), (2) 3½ per cent nickel steel (not more than 0.30 per cent chromium), (3) 55-ton nickel-chromium steel (0.50 to 1.00 per cent chromium), (4) air-hardening nickel-chromium steel, (5) oil-hardening nickel-chromium steel.

In addition there are the B.S.I. 45-ton alloy steel bars (heat-treated) and the 55-ton alloy steel bars, the chemical compositions of

* B.S. Aircraft

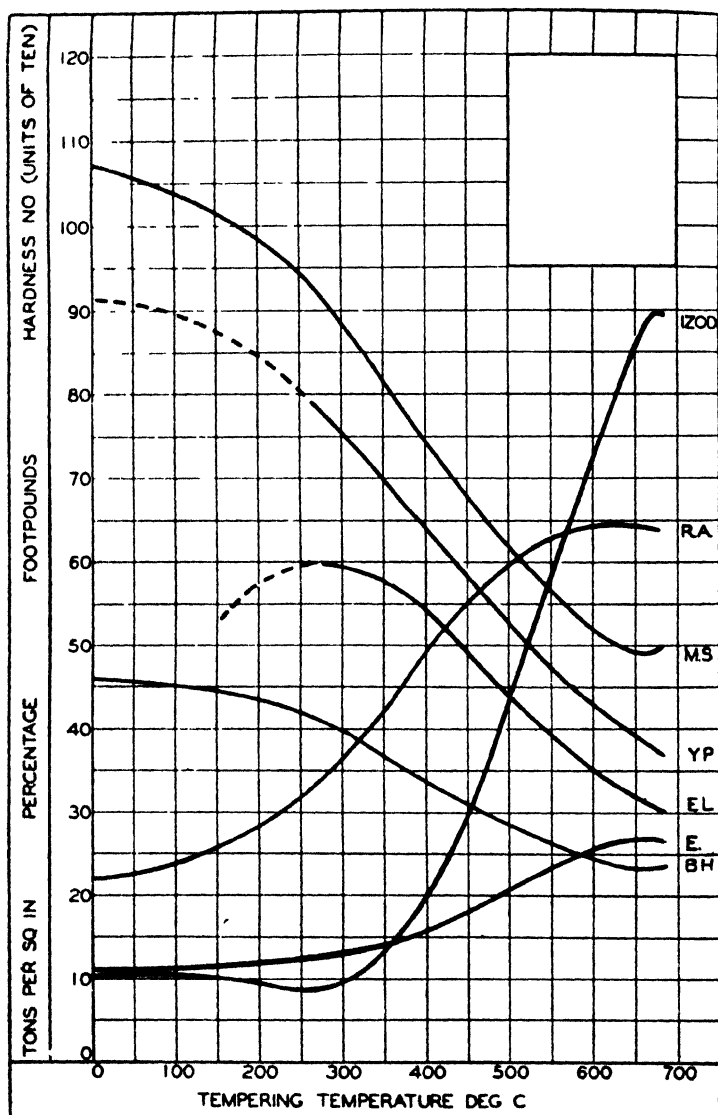


FIG. 107 MECHANICAL PROPERTIES OF NICKEL CHROMIUM MOLYBDENUM (65 TON) STEEL

$1\frac{1}{2}$ in. diameter bars hardened in oil from 830 °C. and tempered

which are not stipulated beyond the fact that the sulphur and phosphorus contents must each not exceed 0.05 per cent. The principal chemical composition and mechanical properties requirements of the steels mentioned in (1) and (2) have been stated already, those for (3) are given herewith.

The B.S.I. 55-ton steel has the following percentage composition: C, 0.28 to 0.34; Si, 0.30 (max.); Mn, 0.45 to 0.70; P, 0.05 (max.); S, 0.05 (max.); Ni, 3.00 to 3.75; Cr, 0.50 to 1.00.

When heat-treated, by hardening in oil from a temperature of 830° C. and tempering at a suitable temperature of 580° C. to 660° C., it has the following mechanical properties:

Tensile strength (tons per sq. in.)	55-65
Yield point (tons per sq. in.)	45 (min.)
Elongation per cent.	18 (min.)
Reduction of area per cent.	50 (min.)
Notched bar impact test (ft. lb.)	40 (min.)
Brinell hardness number	241-311

Nickel-chromium steel is supplied commercially in billets, bars, forgings, stampings, sheets, tubes, etc.

Chromium Steels

These include the low- and high-chromium steels. The former contain chromium up to about 2.5 per cent, with or without the addition of much smaller percentages of molybdenum, copper, etc. Such steels are harder in the untreated condition than carbon steels of similar carbon content, and are also harder and stronger in the heat-treated state than the latter. Chromium also improves the wear resistance and permits larger masses to be hardened satisfactorily throughout.

Chromium steels can be worked, forged, and cast with no more trouble than in the case of ordinary carbon steels.

Steels of the low chromium class are employed in place of carbon steels for various purposes where extra hardness is desired.

File steels are now frequently made from chromium steel, a typical composition containing from 1.2 to 1.5 per cent carbon and about 0.5 per cent chromium.

Ball and roller bearings are usually made of chromium steel. One typical composition has 1.1 per cent carbon, 1.4 per cent chromium, 0.35 per cent manganese, and 0.3 per cent silicon.

This steel, for balls smaller than $\frac{1}{2}$ in. diameter, is heat-treated by quenching from 750° C. in water, and tempering at about 200° C. for half an hour. In the case of larger balls the quenching temperature is 820–840° C. The diamond hardness is about 800.

Chromium steels are also used for dies and stamps employed for pressed work, drawing, trimming, and forging purposes.

A typical low-chromium steel* suitable for dies, mandrels, gear wheels (applicable to surface hardening), and moulds for tyres has the following percentage composition: C, 0.55 to 0.65; Si, 0.30 (max.). Mn, 0.5 to 0.8; Cr, 0.45 to 0.70. When hardened by quenching at 830-850 °C. and tempered at 550-650 °C. it gives a yield stress of 40 tons per sq. in.; tensile strength of 60 to 70 tons per sq. in.; elongation (min.) of 15 per cent, with 40 per cent (min.) reduction of area, 40 ft.-lb. (min.) Izod and 277 to 351 Brinell hardness for specimens made from 1½ in. diameter bars.

Low-carbon (0.12 to 0.18 per cent C) chromium steels are also employed for *case-hardened parts* such as roller bearings, cams, and camshafts; the chromium content in such steels is from 0.9 to 1.20 per cent, with 0.40 to 0.60 per cent manganese. These steels give tensile strengths in the refined and water-hardened condition of 40 to 60 tons per sq. in., with 18 per cent (min.) elongation and 40 per cent (min.) reduction of area. The Brinell hardness varies between 185 and 280.

Chromium-steel castings with excellent mechanical properties are now used in preference to welded and forged steels for many purposes. The addition of 1 to 2 per cent of chromium increases the strength of carbon steels sufficiently to enable a saving in weight to be effected, whilst response to heat-treatment is further improved by the addition of 0.25 to 0.50 per cent of molybdenum. With 6 per cent and upwards, the steel becomes heat-resisting.

The following are typical examples of the compositions of commercial chromium castings†

TABLE 54
CHROMIUM-STEEL CASTINGS

Group	C per cent	Cr per cent	Mo per cent	Use
Ia	0.12-0.20	0.80-1.50	0.25	Case-hardening
Ib	0.20-0.35	0.80-2.00	0.25	For heat-treatment
IIa	0.15-0.25	About 1.0	About 0.5	High-pressure fittings
IIb	0.15-0.25	3.0-6.0	About 0.5	and in the oil industry
III	0.15-0.60	6-16		Heat resistance
IV	0.15-0.30	14-16		Corrosion resistance

* English Steel Corporation Ltd.

† "Chromium Steel Castings," Dr. K. Roesch, *The Metallurgist*, 29th December, 1939.

Group Ia consists of low-carbon constructional steels, which incidentally have good magnetic properties, but are most suitable for cog wheels, sprocket wheels, etc., which are to be case-hardened. Group Ib are used for cast-steel parts in aircraft, their good properties actually leading to a considerable saving in weight. The steel is also weldable, and in this respect the acid steel is said to be better than the basic. For an average composition the mechanical properties, given in the form of curves, are as recorded in Table 55. The advantages

TABLE 55
MECHANICAL PROPERTIES AFTER HEAT-TREATMENT

	Average Type Ib			Type IV, 14 per cent Cr		
	500	600	700	500	600	700
Tempering temperature, deg. C.						
Yield point, tons per sq. in.	63	50	39	67	50	41
Maximum load, tons per sq. in.	76	62	51	76	57	51
Elongation per cent ($l = 5d$)	9	15	21	8	10	14
Reduction of area, per cent	30	42	55		20	40
Impact figure, mkg./cm ²		10	15		2	6

of the addition of molybdenum in promoting depth hardening and in allowing the use of higher tempering temperatures to obtain a given tensile strength with increased ductility are emphasized. The steels of group IIa are used in high-pressure steam plant at temperatures up to 500° C. They are notable for their creep resistance, which is enhanced by the presence of molybdenum. The creep limits at 500° of carbon steel, a steel with 0.5 per cent of molybdenum, and one with 1 per cent of chromium and 0.5 per cent of molybdenum are given as 4.4, 7.6, and 10.1 tons per sq. in. respectively. A casting of a high degree of heat and corrosion resistance is that of type IIb, largely used in oil refinery work at temperatures up to 600° C. Group III contains the heat-resisting steels, frequently used with higher chromium and rather higher carbon content than that given. The maximum admissible temperature at which they may be exposed to furnace gases is stated to rise 18° for every 1 per cent of chromium, from about 700° C. for 6 per cent of chromium to about 1130° C. for 30 per cent of chromium. Group IV contains the corrosion-resisting castings in which it is essential that the chromium should be over 11 per cent (preferably 14 per cent) and the carbon low. A hardening temperature of 950° to 1050° C. must be used.

Chromium Structural Steels

Chromium steels are also *used for certain structural parts, for buildings, bridges, the superstructures of ships, etc., to enable weight saving to be effected over the carbon steels previously employed.*

A typical steel having a tensile strength of 37 to 43 tons per sq. in. with 17 per cent elongation (min.) on 8 in. and 40 per cent reduction of area (min.), and an improved resistance to corrosion, is a copper-chrome steel of the following percentage composition: C, 0.3 (max.); Mn, 0.70 to 1.0; Cr, 0.7 to 1.10; Cu, 0.25 to 0.5; Si, 0.2 (max.); P and S, 0.05 (max.) each. This steel owes its advantage to the fact that the ferrite areas contain alloyed elements which increase the strength of these areas, independently of the carbon content of the steel and in a more effective manner than carbon.

Other structural steels containing chromium which are now employed include those having from 0.4 to 0.6 per cent of chromium, 1.1 to 1.4 per cent of manganese, and 0.7 to 0.9 per cent of silicon. The carbon content ranges from 0.10 to 0.60 per cent. These steels are harder and stronger than the usual structural carbon steels. Tensile strengths as high as 58 tons per sq. in. are obtained in the rolled condition and up to 70 tons per sq. in. heat-treated. They possess high fatigue limits, good ductilities and impact strengths; a fatigue limit as high as 60 per cent of the tensile strength can be obtained.

Chromium steels of 0.45 to 0.75 per cent carbon content are used for *railway locomotive, carriage, and wagon tyres*. According to their carbon and chromium content they can be arranged to give tensile strengths ranging from 50 to 80 tons per sq. in., and are greatly superior in their strength, toughness, and wearing qualities to plain carbon steels.

High-chromium steels, containing from 12 to 18 per cent of chromium, are noted for their marked resistance to corrosion by various attacking media: they are known as "stainless," rust- and acid-resisting steels. Reference is made later in this volume to these steels.

High-tensile Alloy Steels

These steels belong to the complex alloy steel class and include in their compositions such elements as nickel, chromium, vanadium, and molybdenum, in addition to the usual elements, carbon, manganese, and silicon. The high-tensile nickel-chromium steels have already been referred to in this chapter.

There is such a wide range of steels of this class, differing in their compositions, but with the same general high tensile strength properties, that it is only possible to give some typical compositions, mechanical properties, and recommended applications in the present limited space.

The compositions of some typical steels of this class are given in Table 56 whilst the corresponding heat treatments and mechanical properties are given in Table 57. In addition information on the

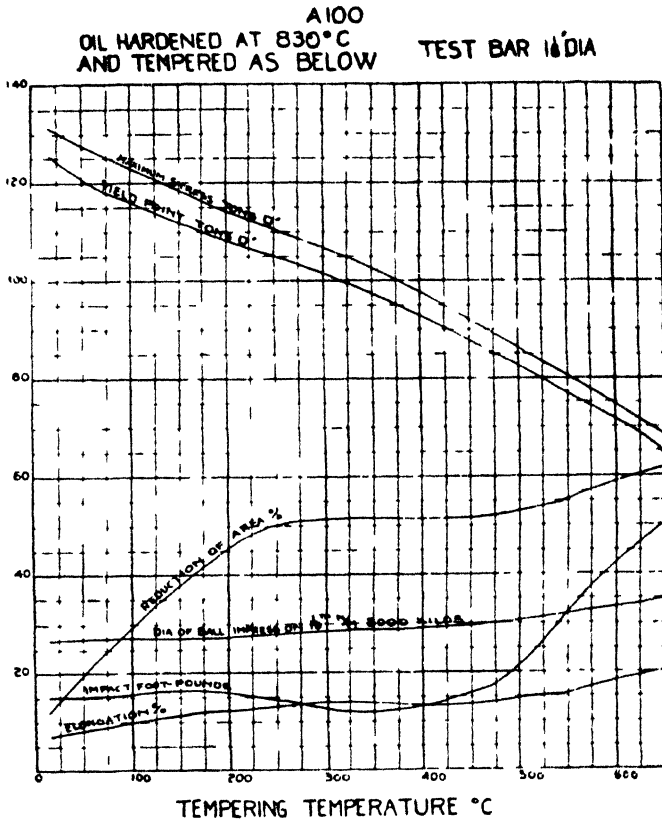


FIG. 108. HIGH-TENSILE STEEL (LOCAL ALLOY A100) FREE FROM TEMPER BRITTLENESS. SUITABLE FOR AUTOMOBILE AND AIRCRAFT ENGINE HIGHLY STRESSED PARTS.

recommended applications of these steels is also included in the latter table. It should be mentioned that many of these steels also conform to BSI and DTD Specifications for automobile and aircraft steels.

TABLE 56

COMPOSITIONS OF TYPICAL HIGH TENSILE STEELS

Designation	Description of Steel	Typical Analysis				
		Carbon	Silicon	Manganese	Nickel	Chromium
A	2½ per cent nickel chrome molybdenum 1	0.30	0.25	0.40	2.25	0.60
B	2½ per cent nickel chrome molybdenum 2	0.40	0.25	0.60	2.25	0.65
C	1½ per cent chromium molybdenum	0.45	0.20	0.60	0.20	1.30
D	3 per cent nickel chromium molybdenum	0.25	0.25	0.40	3.00	1.20
E	Vanadium	0.35	0.25	0.55	3.00	1.20
F	3 per cent nickel chromium molybdenum	0.15, 0.55	0.35	0.30, 0.65	0.30	2.35
G	Chromium molybdenum	0.30, 0.35	0.35	0.50, 0.70	(max.)	1.00-1.50
H	Nickel chromium molybdenum (Vibac) V 45	0.35, 0.45	0.30	0.50, 0.70	(max.)	0.55-0.65
J	Nickel chromium molybdenum (Vags)	0.32, 0.40	0.30	0.50, 0.70	1.30, 1.80	1.20-1.60

A, B, C, D, E, F, G, H, J: Firth & John Brown Ltd. F, G, H, J: English Steel Corporation Ltd.

TABLE 57

HEAT-TREATMENT MECHANICAL PROPERTIES AND APPLICATIONS OF HIGH TENSILE STEELS

Designation	Heat treatment	Tensile strength, lb./sq. in.			Elongation, %			Applications	
		Min.	Typ.	Max.	Min.	Typ.	Max.	Applications	Notes
A	OH S50 1 40 0 0 0	—	—	—	—	—	—	Automotive, truck, aircraft, and gear shafts, gears, and other machine construction	
B	OH S50 1 20 0 0 0 max	—	—	—	—	—	—	Automotive, truck, aircraft, and gear shafts, gears, and other machine construction	
C	OH S50 1 0 0 0 0	—	—	—	—	—	—	Automotive, truck, aircraft, and gear shafts, gears, and other machine construction	
D	OH S50 1 600 0 0 0	—	—	—	—	—	—	Automotive, truck, aircraft, and gear shafts, gears, and other machine construction	
E	OH S50 1 5 0 2 0 0	—	—	—	—	—	—	Automotive, truck, aircraft, and gear shafts, gears, and other machine construction	
F	OH 900 1 0 0 0 0	—	—	—	—	—	—	Automotive, truck, aircraft, and gear shafts, gears, and other machine construction	
G	OH S70 1 0 0 0 0	—	—	—	—	—	—	Automotive, truck, aircraft, and gear shafts, gears, and other machine construction	
H	OH S25 1 20 0 0 0	—	—	—	—	—	—	Automotive, truck, aircraft, and gear shafts, gears, and other machine construction	
J	OH S30 1 20 0 0 0	—	—	—	—	—	—	Automotive, truck, aircraft, and gear shafts, gears, and other machine construction	

* Minimum value.

* Brinell hardness 277-532.

Steel Sheets for Various Purposes

Sheet steel has a wide range of industrial application, and for this reason is supplied in a number of different qualities and finishes.

The plain carbon sheet steels are available with carbon contents ranging from about 0.06 to 0.45 per cent. These steels are usually made by the open-hearth, electric furnace, or crucible processes, cold-rolled, pickled, and annealed. Typical compositions and *minimum* tensile test values for such steels are given in Table 58.

TABLE 58
COMPOSITIONS AND STRENGTH PROPERTIES OF CARBON SHEET
STEELS

Material	Carbon	Manganese	Phosphorus (max.)	Sulphur (max.)	Yield Point Tons per sq. in.	Tensile Strength Tons per sq. in.	Elongation per cent on 4 in.
Extra-soft carbon	0.05-0.15	0.30-0.60	0.015	0.050	13.5	22.0	25.0
Soft carbon	0.15-0.25	0.30-0.60	0.015	0.050	16.0	27.0	22.0
Soft carbon	0.20-0.30	0.50-0.80	0.015	0.050	20.0	32.5	18.0
Half-hard carbon	0.25-0.35	0.50-0.80	0.015	0.050			
Half-hard carbon	0.30-0.40	0.50-0.80	0.015	0.050			

Alloy steels are also supplied in sheet form and, when annealed, have similar properties to the rod and bar steels of the same compositions. The effect of rolling is to increase the tensile strength and reduce the elongation as compared with the annealed values. These alloy sheet steels are amenable to heat-treatment in a similar manner to the steels of corresponding compositions mentioned earlier in this chapter. Such steels are employed for pressed parts where high strength properties are required, e.g. automobile and aircraft fittings.

The stainless steels are also made in sheet form, whilst bullet- and shrapnel-proof steels of manganese, nickel-chrome, chrome-vanadium, etc., suitably heat-treated, are widely used for military purposes. The tensile strengths of these plates vary from about 70 to 120 tons per sq. in. and they are exceedingly tough and hard; the Brinell hardnesses range from about 400 upwards. In this connection a nickel-chrome plate of 4 S.W.G. (0.232 in.), weighing 9.3 lb. per sq. ft., will resist penetration at a range of 500 yd. by an armour-piercing machine-gun bullet (with hardened steel core); a special alloy steel plate of 10 mm. thickness will resist penetration at 60 yd.

The ordinary "black sheets" are prepared in several forms—namely, (1) pickled, cold-rolled, and close annealed; (2) pickled and

close annealed: (3) close annealed, and (4) close rolled and close annealed—or what is commonly designated the C.R.C.A. quality.

The sheets are usually hydraulically flattened and are supplied in various finishes to suit special requirements.

Thus, for electrical purposes, the steel sheets are specially prepared: for enamelling the sheets are close annealed, hydraulically flattened, resheared, and resquared.

The "special blue" C.R.C.A. steel* is hydraulically flattened and resheared. It is a high-class well-finished sheet with a dense blue-black colour. The sheets will work up in any direction and the oxide colouring does not break off.

For lagging boilers and other heating plant a special blue lagging steel is supplied. Usually these bright blue sheets are rather hard in temper and will not work up very well—they can, however, be curved and bent to relatively large radii satisfactorily.

Specifications for sheet steels of this class require that test strips, cut in any direction from the sheet, shall conform with certain minimum conditions of yield stress, tensile strength, elongation, and reduction of area.

It is now general to stipulate a bend test for strips cut in any direction: the strips should be capable of being hammered over, or otherwise bent, cold, through an angle of 180°—that is to say, parallel to the original direction, to a radius equal to the thickness of the plate, without cracking on the outer surface of the bend. A further test, often specified, stipulates that strips 1½ in. wide, cut from the sheets, and with the edges rounded, shall stand reverse bending cold, through an angle of 90°, for not less than three complete reversals without fracture.

It is sometimes desirable to specify that a welded joint of the sheet material shall be tested in tension, and that the efficiency of the weld shall be not less than from 80 to 85 per cent of that of the unwelded metal.

Sheet Steels for Pressings

Sheet steels suitable for cold pressing have relatively low carbon content since the ductility is reduced with increasing carbon in steels. In instances, however, where greater tensile strength is required from the pressing, steels of higher carbon content are employed, but must be normalized, annealed, or spheroidized before pressing; for multi-stage pressing operations these processes must usually be repeated between the stages. A finer grained structure is considered much better for cold pressing purposes than a coarser grained one, since the surface

* Messrs. Baldwin Ltd., Swansea.

finish obtained is much smoother; the grain must not be too fine as the steel will be too hard for plastic deformation, so that a compromise is necessary in selecting the type of steel and the softening process for cold press work.

The compositions and strength properties of typical steels recommended for cold pressing purposes are given in Table 59;* the various purposes for which such steels are suitable are also indicated.

Automobile Sheet Steels

Sheet steels are now widely employed in the automobile industry for body panels, dashboards, and pressed sheet metal parts.

Most of the steel used by motor body builders is mild Siemens-Martin sheet steel, protected against oxidation with a coating of non-rusting metal or specially prepared for subsequent protection by paint or enamel. The qualities supplied,† in descending order of cost, are—

1. *Tinned Sheets (Rustless)*. These are mild steel sheets coated with pure tin by a special process, leaving them with a smooth bright surface. They are used both for body panels and petrol tanks. In the latter respect, owing to the use of doped petrols or benzole mixtures, a heavily tinned sheet for petrol tanks is advisable.

2. *Tin-terne Sheets (Rustless)*. These are mild steel sheets coated with an alloy of tin and lead. They are used chiefly for bodywork, bonnets, and wings. A special "copper-soft" quality is made for beating and stamping.

3. *Lead-coated Sheets (Rustless)*. In this case the mild steel sheets are coated with pure lead, with a small tin content. They require no "rubbing down" or "filling" before painting. A special "copper-soft" quality is made as in No. 2.

4. *Mild Steel Sheets (Uncoated)*. These are of Siemens-Martin mild steel, but are not coated with any protecting metal. They are supplied in four grades suitable for motor panels and subsequent painting, as follows: (a) Best bright silver-finish steel sheets hydraulically flattened and resheared. The smooth surface renders these particularly applicable for press work. (b) Specially pickled C.R.C.A. steel sheets, copper-soft quality for beating and stamping. These have a whitish finish over the centre of the sheet, and a narrow margin of blue anneal round the sides. (c) Steel sheets C.R.C.A. hydraulically flattened, resheared, and resquared, dead-flat finished dark blue colour. (d) Steel sheets C.R.C.A., copper-soft, quality, annealed.

* Park Gate Iron & Steel Co. Ltd.

† Messrs. Baldwin Ltd., Swansea.

TABLE 39

SHEET STEELS FOR COLD PRESSING PRODUCTS

P G Mark	Nomenclature	Tensile Properties			Typical Tests			Typical Applications
		$\sigma_{0.2}$ (max)	$\sigma_{0.2}$ (max)	$\sigma_{0.2}$ (max)	Yield strength in sheet	Formability	Elongation	
101	Lead soft steel	0.07-0.12	0.10	0.0	0.40-0.70	20-25%	24%	41
102	Special deep-drawn steel	0.07-0.12	0.04	0.04	0.3-0.60	20-25%	24%	41
102A	0.10-0.15 carbon steel	0.10-0.15	0.1	0.0	0.40-0.70	20-25%	24%	41
102B	0.15-0.20	0.15-0.20	0.15	0.0	0.40-0.70	20-25%	24%	41
103	0.20-0.25	0.20-0.25	0.1	0.0	0.40-0.70	20-25%	24%	41
104	0.25-0.30	0.25-0.30	0.20	0.0	0.40-0.70	20-25%	24%	41
105	0.30-0.35	0.30-0.35	0.20	0.0	0.40-0.70	20-25%	24%	41
106	0.35-0.40	0.35-0.40	0.20	0.0	0.40-0.70	20-25%	24%	41
107	0.40 carbon high manganese steel	0.40-0.50	0.20	0.05	0.45-0.70	20-25%	24%	41

• N = normalized

A = annealed

7

spheroidized

General cold pressing work for automobiles, light equipment miscellaneous hardware etc.

Difficult cold pressings such as wire wheel hub shells, pump cases, bushings, tapered disc wheels, etc. (thinner than for rollers etc.)

Automobile parts not highly stressed: seamless hardware, ball and roller bearings, gear cases, ball and roller bearings, etc.

Basic frame, tapered disc wheels, wire wheel hub shells, brake drum, axle and brake housing, etc. (thinner than for rollers etc.)

The most regular steel for cold pressed brake drums and bearings etc. for commercial vehicles.

Brake drum, center of spring hub shell, and other 11 mm for axle nobles.

Higher tensile brake drums for heavy commercial vehicles, brake drum liners for aircraft, etc.

High tensile frame, frame, brake drum, etc. of improved rigidity and for welding properties.

Special Tinned Sheets

The best tinned steel plates are made from Siemens-Martin open hearth soft steel bars. They are well cleaned and pickled preparatory to coating with tin. They are then coated with pure refined tin by a special process involving, during the preliminary stages of coating, the leaving of the plates to soak for some time in successive baths of molten tin. No flux is used at any time during the tinning process, but pure palm oil is employed to prevent oxidation of the surfaces. Although more costly than the ordinary methods, the results are superior, there being a solid coating of tin spread over the oxidizable steel, a real amalgamation of the tin and steel being obtained. The deposit of tin by this method is from two to six times greater than with ordinary Welsh tin plates.

Iron-cored Steel

For certain engineering and industrial applications it is an advantage to employ a composite material consisting of a wrought iron

interior and a steel exterior, thus obtaining the ductility and fibrous toughness of the former with the tensile strength and wearing properties of the latter. Steel rod and wire have been made with iron fibres combined with mild steel as shown in Fig. 109. The iron and steel rod composite block used for this purpose is heated to a bright red heat and rolled down to the size required.

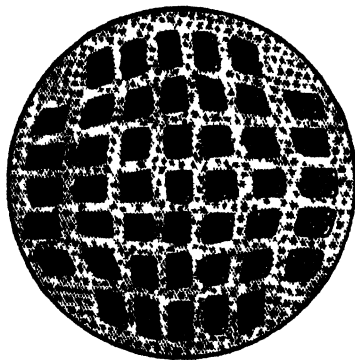


FIG. 109. COMPOSITE STEEL AND IRON ROD. THE DARK AREAS REPRESENT THE IRON.

Laminated steel and iron is sometimes used in the form of rods for parts subject to vibration and shock, e.g. cylinder studs, piston rods, draw bars, coupling links, axles, chains, etc.

Laminated steel plate of the types shown in Figs. 110 and 111 is employed for the plates of safes; the laminations consisting of hard steel and soft steel respectively.

Fig. 110 shows a five ply steel containing three layers of iron or extremely soft steel with two outer layers of hard steel, such as chromium steel. The latter, when hardened in water from 770 °C, is impervious to high powered drilling. The soft material clogs the drill whilst the hard steel splinters or dulls the cutting edge.

Fig. 111 shows a laminated steel consisting of hard and soft steel, known as Turner's Safe Plate. After hardening at 800° C. it has an impenetrable face that will resist the most determined attempts at drilling. Both the plates illustrated are supplied in a condition easy to work up, hardening being done afterwards.

Composite Die Steels

Composite steels are often used for making press tools, since it is thus possible to use a steel capable of taking a considerably greater degree of hardness in the composite form than would be desirable or practicable in a solid steel. Improved results are thus obtained and tools of this metal give appreciably longer life and service. Bearing in mind the heavy initial cost of most press tools, this extra life represents a definite economy. Further, the soft backing of the hardened steel acts to some extent as a cushion when the die is in use, thus preventing breakages. After hardening, a tool which may have "moved" slightly can be *machined flat on the soft underside* in a fraction of the time needed to grind a hardened homogeneous die steel.

In certain circumstances such as with intricate dies in which high output is required and the material to be worked is very thin and fine limits must be adhered to, a *solid steel* will give the most satisfactory results.

A number of composite steels, known as the Eclipse,* are now available for die-making purposes. Typical products include: (1) A combined iron and straight carbon crucible steel suitable for hardening in water, this material being recommended for all straight-forward press tool work. (2) A composite iron and crucible alloy water-quenching steel, the latter being a tungsten-chrome alloy, this gives greater hardness and toughness than the steel (1). (3) A

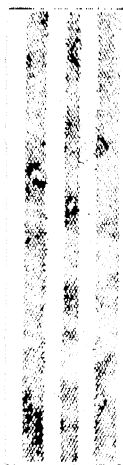


FIG. 110
FIVE PLY
LAMINATED
STEEL PLATE

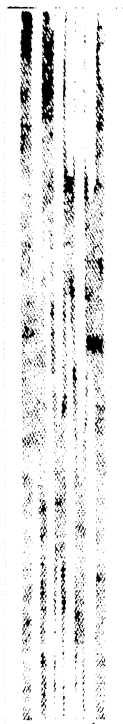


FIG. 111
TURNER'S
LAMINATED
SAFE PLATE

* J. Neill Ltd., Sheffield.

crucible oil-hardening composite steel of considerable toughness and long life.

Composite steels are also made for other purposes where a soft body or shank combined with a proportion of hard alloy or carbon steel, laid in almost any position, is required, either for cutting edges or wearing surfaces.

Celfor Steel. Celfor* is the name applied to a special composite steel having a soft core and outer case of 1.0 per cent carbon content

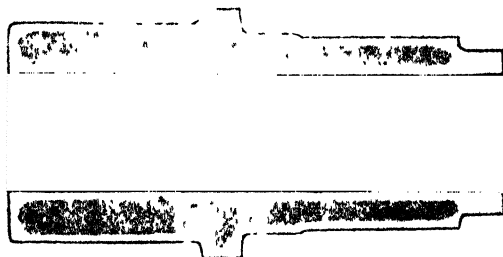


FIG. 112. CELFOR STEEL GUIDE BUSH

which, when heated to the appropriate hardening temperature and quenched in water or brine, gives an extremely hard case, whilst retaining a tough core. It gives equivalent results to those obtained by case-hardening carbon steels, but with a greater depth of hardened layer. The steel in question is recommended for tools subject to severe abrasion and deformation, such as pistons, rods, sleeves, and bushes for pneumatic tools, gudgeon pins, small rolls, pestles and mortars, dies, etc.

Two-ply Stainless Steel

This steel is made from a composite ingot, the surface of the stainless steel part of the ingot having been polished before the mild steel is applied. The ingot is then rolled down into sheets of the desired thickness; in this connection the relative thicknesses of the two metals can be varied to suit the purposes for which the final product is required.

The stainless steel provides adequate corrosion, heat, and abrasion protection to the mild steel beneath and for this reason it should be used as a continuous sheet and not for applications requiring piercing the metal, as in screens or grids.

* Sanderson Bros. & Newbould Ltd., Sheffield.

The principal advantage of this composite steel is that whilst giving adequate strength properties combined with a high degree of corrosion-resistance, it is at least 50 per cent cheaper than the solid stainless steel. Its potential applications include use for tanks, vats, kettles, and digesters in chemical processes, and in the mining, processing, food, and metal-working industries.

The material can be deep-drawn, stamped, formed, and welded, and it offers advantages in the form of pipes, bars, and other shapes as well as in the sheet form described.

Nickel-clad Steel Plates

Nickel rolled on steel, in the form of nickel-coated strip and sheet now available for industrial purposes, has all the corrosion-resisting properties of commercial hot-rolled sheet nickel. The nickel is firmly bonded to the steel and the composite plate is such that it can be treated as a solid steel plate for fabrication purposes. As manufactured the nickel surface is covered by a thin, strongly adherent and glossy oxide film, dark olive-brown in colour, which has excellent corrosion-resistance qualities; if desired the film can be removed and a bright surface exposed. The thickness of the nickel can be varied at will to suit requirements; the most widely used variety is a plate, $\frac{1}{4}$ in. thick, with 10 per cent thickness of nickel on one side.

Typical applications of nickel-clad steel plates include tanks, kettles, containers, etc., for use in the soap, dye, cellulose, plastic, laundry, varnish, and food-stuff industries. The first commercial equipment made was an 8000-gallon tank railway car for transporting liquid caustic soda.

Nickel-coated Strip

The thinner materials, known as nickel-coated steel sheet and strip, consist of sheet or strip steel covered by a thin layer of malleable nickel, both metals being firmly bonded together over their entire surface of contact. In their production a composite slab is used, consisting of a nickel plate and a steel plate suitably held together. This composite slab is heated to the required temperature and then hot rolled to obtain the necessary bond. The final reducing operations are done by cold rolling, and the finishes obtained are those of cold-rolled nickel and cold-rolled steel, namely, bright and smooth.

The nickel coating may be either on one side of the steel or on both sides, while the thickness of the nickel may be arranged to suit the service conditions under which the material is to be used.

The malleable nickel coating is non-toxic, corrosion-resisting, hard wearing, and capable of taking a very high polish. These properties have led to the use of the nickel-coated materials for such applications as chocolate moulds, trays, parts of electric heating and cooking apparatus, polishing plates for celluloid, sandwich boxes, parts of miners' electric safety lamps, and many similar purposes.

CHAPTER VI

SPECIAL ALLOY STEELS

In addition to the alloy steels mentioned in the previous chapter there are certain steels or groups of steels having important special applications in engineering and industry. Those that are dealt with in the present section include the following: (1) Stainless or Rust- and Acid-resisting Steels; (2) Heat-resisting Steels; (3) Manganese Steels; (4) High-speed Tool and Die Steels; (5) Spring Steels; (6) Valve Steels.

I. Stainless Steels

The original rust- and acid-resisting steel discovered by Brearley, of the Brown-Firth Laboratory, Sheffield, was a high-chromium steel of the following approximate percentage composition: C, 0.24; Mn, 0.30; Cr, 13.0; Fe, 86.46. It was produced in the electric arc furnace and could be rolled, forged, and heat-treated.

The average mechanical properties of small bars, oil hardened at 960° C. and tempered at 700° C., were as follows: Tensile strength, 48 tons per sq. in.; yield point, 39 tons per sq. in.; elongation on 2 in. \times 0.564 in. test piece, 25 per cent; reduction of area, 63 per cent; and Izod impact value, 86 ft.-lb.

This steel, in the heat-treated condition, was found to have marked resistance to corrosion by the atmosphere and a range of acids and alkaline solutions, and was therefore employed for such purposes as cutlery, surgical and dental instruments, small engineering and chemical fittings, etc. In the early stages of their development stainless steels were used for a comparatively small number of applications, for the dimensions of the parts which could be cast or fabricated were limited. Since this period, however, there has been a considerable amount of investigation work resulting in the discovery of many different kinds of corrosion-resisting steels, so that it is now possible to obtain such steels in practically every form in which carbon steels are available. It is characteristic of these steels that they all contain a chromium content of over 12 per cent. An idea of the present wide range of these steels can be obtained from the fact that the pioneer firm responsible for the development of rust- and acid-resisting steels lists about a dozen different stainless steels and irons having tensile strengths in the heat-treated condition of 30 to over 100 tons per sq. in. and Brinell hardnesses of 140 to 550.

Classification of Stainless Steels

The commercial stainless steels and irons can be classified broadly into two groups, namely, the martensitic and austenitic ones. The first group includes the following corrosion-resisting steels—

A. Plain chromium steels containing 12 to 20 per cent chromium, with varying carbon content up to 0.80 per cent.

B. High-chromium low-nickel steels with 16 to 20 per cent chromium, 2 per cent nickel, and varying carbon content from 0.1 to 0.2 per cent.

The second group includes—

C. Austenitic chromium-nickel steels with or without additions of special elements such as tungsten, titanium, molybdenum, and copper.

The mechanical properties of these steels* are given in Table 60. Figs. 113 and 114 illustrate the microstructure of stainless steel in the hardened conditions.

In regard to the steels in groups A and B, these can be hardened by heat-treatment, as the results given in Table 60 show, and they are *magnetic*. The steels in group C include the high-nickel ones, known as 18/8, containing 18 per cent chromium and 8 per cent nickel with small additions of special elements. These steels *cannot be hardened* by heat-treatment and are *non-magnetic* in the soft condition. Similarly, the 12/12 non-corrosive steels, containing about 12 per cent each of chromium and nickel, *cannot be hardened* and are *non-magnetic*.

In regard to the order of corrosion-resistance, the steels in group C are the best, with those in group B next and group A last.

Physical Properties of Stainless Steels

The *specific gravities* of the steels in the groups A, B, and C average 7.74, 7.70, and 7.96 respectively. There is, however, a range of variation in the specific gravities of the steels in group C, namely, from 7.90 to 8.10, according to their composition.

The *coefficients of linear expansion* from 20° to 100° C., average, for the three groups A, B, and C, 107×10^{-7} , 104×10^{-7} , and 170×10^{-7} . As the coefficient for ordinary steel is about 105 to 115×10^{-7} , it will be observed that whilst the martensitic stainless steels have about the same expansion coefficient, the austenitic steels in group C—to which the well-known “*Staybrite*” steel belongs—have *about 50 per cent greater expansion*. This is an important item in connection with the welding of such steels and their use at temperatures above atmospheric in conjunction with ordinary steels where differences of expansion may have important effects.

* “Heat-, Rust- and Acid-resisting Steels,” Dr. W. H. Hatfield, F.R.S., *Proc. Chem. Eng. Congress of World Power Conference*, 1936.

FIG. 113. STAINLESS STEEL, HARDENED AND TEMPERED $\times 500$ FIG. 114. STAINLESS STEEL, CUTLERY QUALITY, HARDENED
AND LIGHTLY TEMPERED $\times 500$

The *thermal conductivities* for groups A, B, and C average, respectively, 0.048, 0.040, and 0.032 C.G.S. units. From the latter result it will be seen that the thermal conductivity of group C steel is appreciably lower than for the other, and also ordinary steels.

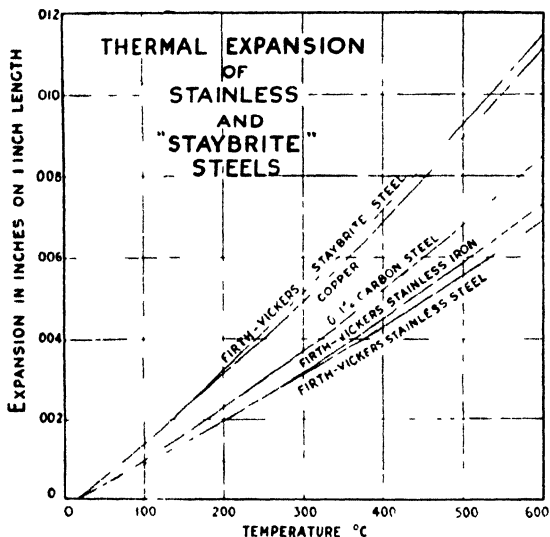


FIG. 115

The respective average *electrical resistivities* for the three groups of steels are, 55, 72, and 72 microhms per c.c. It should be mentioned that the last two steels given in group C, Table 60, have much higher resistivities than the other six steels in this group, the values being 98 and 82 respectively.

The *maximum permeabilities* for the first three steels in group A are 500, 650, and 75 C.G.S. units respectively; and for the steel in group B, 210. The values for the steels in group C (non-magnetic) average 1.005 to 1.03 C.G.S. units for the first six. The last but one steel is slightly magnetic (B.H. = 3500 for 150) and the last steel has a maximum permeability value of 4 to 10 C.G.S. units.

Heat-treatment and Mechanical Properties

It is not possible in the space available to deal with each of the better-known and more widely used stainless steels, so that *three typical steels* only can be considered, from the three groups previously referred to.

TABLE 60

CLASSIFICATION AND PROPERTIES OF CORROSION-RESISTING STEELS (HATFIELD)

Designation	Typical Analysis						Mechanical Properties						
	C	Cr	Ni	W	Ti	Mo	Condition	Yield Point Tons per sq. in.	Max. Stress Tons per sq. in.	Elonga- tion per cent on 2 in.	Reduc- tion of Area per cent	Young's Modulus Elasticity Tons per sq. in.	Brinell Hardness
GROUP A Low- chromium	0.10 max.	12.0-15.0	—	—	—	—	Heat-treated and fully tempered or annealed	15-25	30-40	30-40	50-60	13,400	140-190
	0.15 max.	12.0-15.0	—	—	—	—	Hardened and fully tempered	25-35	40-50	20-30	50-60	13,700	200-240
	0.20-0.35	12.0-14.0	—	—	—	—	Doc. and highly tempered	—	—	—	—	—	450-550
	0.40-0.50	12.0-14.0	—	—	—	—	Doc. and highly tempered	—	—	—	—	—	550
GROUP B Low-nickel high-chromium	0.15	16.0-20.0	1.5-2.5	—	—	—	Hardened and tempered	35-50	50-60	15-25	40-60	13,500	240-290
GROUP C Chromium- nickel with additional elements	0.10	12.5	12.5	—	—	—	Fully soft-tem	15-17	35-40	40-60	40-60	12,900	130-150
	0.15 max.	18.0	8.0	0.5-1.0	—	—	Fully soft-tem	15-18	35-45	40-60	40-60	12,900	160-180
	0.15 max.	18.0	8.0	0.5-1.0	0.5-1.0	—	Fully soft-tem	16-20	40-50	35-50	40-60	13,000	160-200
	0.07 max.	18.0	10.0	—	—	2.5-4.0	Fully soft-tem	15-18	40-45	40-60	40-60	13,200	150-180
	0.07 max.	15-16	10.0-11.0	—	—	1.0-1.5	Fully soft-tem	15-18	40-45	40-60	40-60	12,800	150-180
	0.15 max.	10-14	35.0-37.0	—	—	—	Fully soft-tem	14-17	35-45	40-60	40-60	12,800	130-150
	0.20-0.30	—	—	—	—	—	Fully soft-tem	22-26	40-50	25-40	40-60	13,000	160-200
0.25	20.0	9.0	—	1.3	—	Fully soft-tem	26	45	30	55	13,000	220	

The first of these is the steel conforming to the *B.S.I. Specification S.62, for corrosion-resisting steel* of 46 to 62 tons per sq. in. and 207 to 235 Brinell hardness in the fully tempered or softer condition.

The following is the standard specification percentage analysis of the steel in question: C, 0.15 to 0.35; Si, 0.50 (max.); Ni, 1.0 (max.); Cr, 12.0 (min.). The steel is supplied in the form of bars and forgings.

A typical steel of this class, which is known as the *medium-tensile rustless* one, when oil-quenched at 960° C. and tempered at 700 to 750° C. gives a yield point of 25 to 40 tons per sq. in.; tensile strength of 40 to 55 tons per sq. in.; elongation of 30 to 20 per cent; and Brinell hardness of 200 to 240.

The effect of tempering this steel, after oil-hardening at 960° C., at different tempering temperatures is shown in the following table

TABLE 61
HEAT-TREATMENT AND PROPERTIES OF MEDIUM-TENSILE
STAINLESS STEEL

Tempered	Yield Point Tons per sq. in.	Max. Stress Tons per sq. in.	Elonga- tion per cent	Izod Impact ft.-lb.	Brinell Hardness Number
500	90.7	98.2	15	12	430
550	72.8	79.7	17	20	364
600	51.4	60.5	20	27	277
650	43.3	52.3	22	65	235
700	41.3	49.1	26	69	223
750	36.6	45.9	30	80	202

From these results it will be observed that a maximum tensile strength of nearly 100 tons per sq. in., with a Brinell hardness of 430, is obtained in the lightly tempered condition.

When this grade of steel is employed for *cutting instruments*, e.g. cutlery, surgical and dental instruments, it is oil-quenched at 950° C. and tempered at about 180° C. A typical steel, namely, Firth's F.H. cutlery grade, in thin sections gives a maximum tensile strength of 108 tons per sq. in. and Brinell hardness of 534.

The *shear stress at yield point* for the steel (O.H., 960° T., 700° C.) is 26 tons per sq. in. The *maximum shear stress* is 33 tons per sq. in. and the number of degrees of twist on $\frac{1}{2}$ in. diameter \times $1\frac{1}{2}$ in. parallel shaft is 478.

The corresponding tensile strength of the steel in the above condition is 49 tons per sq. in.

The *fatigue limit*, for 10 million reversals of stress without breaking, is 22 tons per sq. in.

The *modulus of elasticity* is 13,700 tons per sq. in.

The *second typical steel* selected is one conforming to the *B.S.I. Specification S. 80 for aircraft material*. It has the following percentage composition: C, 0.25 (max.); Si, 0.50 (max.); Mn, 1.0 (max.); Ni, 1.0 (min.); Cr, 16.0 to 20.0, and a tensile strength of 50 to 60 tons per sq. in., with a minimum elongation of 15 per cent and Izod value of 25 ft.-lb (min.).

It has a corrosion resistance which approaches that of the austenitic steels in group C and can easily be machined. It is also characterized by its resistance to *electrolytic corrosion* when in contact with other dissimilar materials such as brasses and graphite packings. This steel is used for highly stressed aircraft and general engineering fittings and for stressed rods and shafts subjected to corrosive attack. The effect of tempering this steel at different temperatures after oil-hardening at 950° C. is shown in Table 62

TABLE 62
HEAT-TREATMENT AND PROPERTIES OF "S 80" STAINLESS
STEEL (FIRTH S)

1½ in. dia. Bar, O.H. 950° C. 22 S.W.G. Strip, A.H. 950° C.									
	T 500° C	T 550° C	T 750° C	T 450° C	T 550° C	T 650° C			
Yield point, tons per sq. in.	58	46	42	63	57	38			
Max. stress, tons per sq. in.	66	55	52	70	66	50			
Elongation, per cent	18	22	25	9	10	12			
Red. of area, per cent	49	56	62						
Brinell hard- ness number	302	255	241	321	302	229			

The *shear stress at yield point* (O.H., 950° C., T, 550° C.) is 28.4 tons per sq. in. and the maximum shear stress 35.7 tons per sq. in. The degrees twist on ½ in. diameter × 1½ in. parallel shaft was 400.

The *fatigue strength* of the steel, heat-treated as mentioned above, for 10 million stress reversals without fracture was 24 tons per sq. in.

The *modulus of elasticity* was 13,700 tons per sq. in.

The *specific gravity* of this steel is 7.70.

The last typical steel to be dealt with here is the *austenitic one*, known as *Staybrite*. This is made in different qualities for various purposes, such as plant and vessels made by welding, domestic ware,

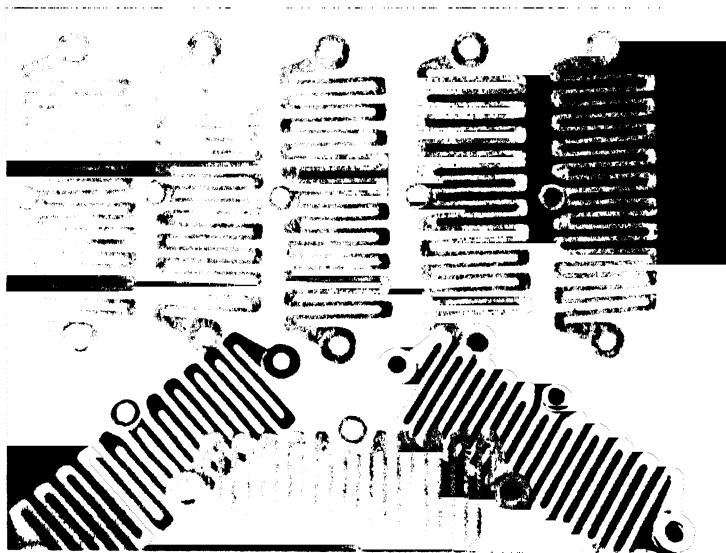


FIG. 116 CAST STAYBRITE STEEL RESISTANCE GRIDS

decorative purposes, deep-drawing, chemical plant, etc. The general-purpose steel known as FST is perhaps the most widely used and so will be considered here.

This steel contains 18 per cent of chromium and 8 per cent of nickel and has a tensile strength of 37 to 45 tons per sq. in. in the normal heat-treated condition, with a minimum yield point of 15 tons per sq. in., elongation of 60 to 40 per cent, and Brinell hardness of 160 to 180.

Although this steel cannot be hardened by heat-treatment, it can be hardened by cold working, as the results given in Table 63 show.

The *yield point* and *maximum shear stresses* of Staybrite steel in the normal condition, corresponding to a tensile strength of 37 to 45 tons per sq. in., are 9.5 and 39.0 tons per sq. in., with 460 twist on $\frac{1}{8}$ in. diameter $\times 1\frac{1}{2}$ in. parallel shaft.

The *fatigue strength* in the same condition for 10 million reversals of stress without breaking is 17 tons per sq. in.

TABLE 63
EFFECT OF COLD WORKING ON STAYBRITE STEEL PROPERTIES

	20 S.W.G. Sheet		16 S.W.G. Wire
	Cold Rolled (1)	Cold Rolled (2)	Cold Drawn
Yield point, tons per sq. in.	52	69	75
Max. stress, tons per sq. in.	58	83	95
Elongation, per cent. .	30	6	6
Gauge length	2 in.	2 in	1 in

The *modulus of elasticity* is 12,900 tons per sq. in. (softened) and 11,000 to 12,900 tons per sq. in. in the cold-rolled or drawn condition.

The *specific gravity* is 7.93, or 494 lb. per cu. ft.

The *thermal conductivity* at 20 and 100 °C. is 0.036 and 0.039 C.G.S. units respectively.

The *coefficient of linear expansion* from 20 to 100 °C. is 170×10^{-6} .

The *electrical resistivity* at 20 and 100 °C. is 72 and 78 microhms per c.c. respectively.

Applications of Stainless Steel

Although some information has already been given on this subject, the following summary of typical applications may be found useful for reference purposes -

Medium-tensile rustless steels (Group A), supplied as forgings, drop stampings, bar, sections, wire, strip, sheet, and castings, are employed for steam, hydraulic, and oil-refinery pump and valve components; highly stressed turbine blading; high-pressure steam valves and seatings; hydraulic pump barrels, rams, and valves; stressed bar aircraft fittings, nuts and bolts; dies for moulding rubber and synthetic materials, e.g. bakelite, and general engineering details, subject to corrosive attack.

The medium-carbon cutlery grade, e.g. Firth's F.H., is employed for cutlery, surgical instruments; dental instruments; bacon slicing and other knives used in the manipulation of foodstuffs; various edge tools; hardened rolls, springs, and instrument details; ball-bearings, ball- and roller-bearing races (a special grade of stainless steel is used for these bearing parts).

High-chromium low-nickel stainless steel (Group B). This steel is

supplied as forgings, drop stampings, bar, sections, sheet, strip, wire, and castings, to various specifications, including B.S.I. and D.T.D.

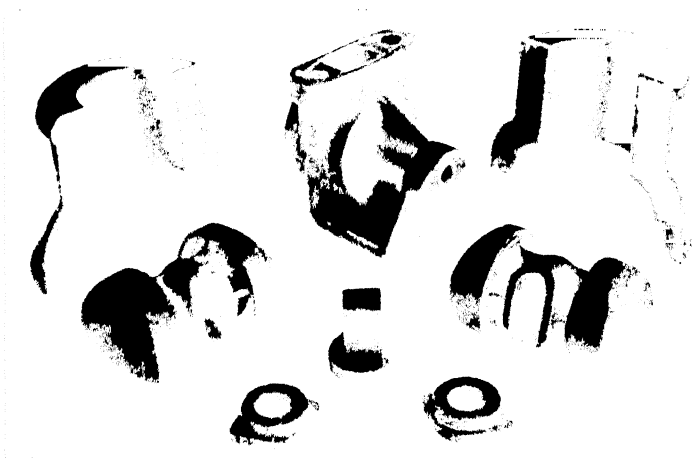


FIG. 117. MAXILVRY STAINLESS STEEL CASTINGS AND GLANDS, DISC VALVE, HALF COLLARS AND NUTS
(EDGAR ALLEN, LTD.)

ones. It is employed for aircraft and automobile pump spindles, pump parts for chemical plant, motor-boat propeller shafts; highly stressed bolts, nuts, and seaplane fittings. In general this steel is used



FIG. 118. WATER TURBINE IMPULSE WHEEL IN STAINLESS STEEL

for more highly stressed parts requiring a slightly greater resistance to corrosion than the steels previously given.

Austenitic chromium-nickel steels (Group C). As these possess the greatest resistance to corrosive attack, combined with good tensile

strength properties, they have a wide field of application in the chemical and other industries.

The Staybrite F.S.T. grade previously mentioned is available in various forms, and is recommended for all types of chemical plant, storage and transport tanks for the chemical industry, dairies, breweries, etc.; for vats and racks in the dyeing industry; ship's fittings;

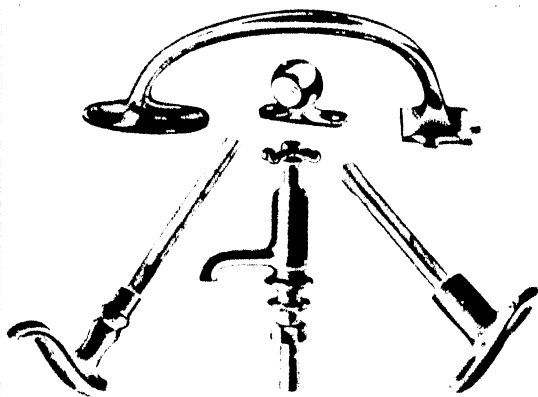


FIG. 119. DOMESTIC AND CAR FITTINGS IN STAYBRITE STEEL.

architectural purposes and internal decoration; mirrors and reflectors; road studs; domestic hardware and ornamental articles.

There is a special grade of this austenitic group, suitable for deep-drawing purposes for hollow-ware and vessels for domestic and decorative purposes. Another grade of high-chromium high-nickel steel is made specially for chemical plant of welded construction and for aircraft welded fittings where it is necessary to *employ parts welded together without subsequent heat-treatment*. This steel of which Staybrite F.D.P. is a good example can also be used for certain *high temperature plant* as it resists scaling up to about 800° C.

Improving Machinability of Austenitic Steels

The stainless nickel-chromium steels of the 18-8 class are difficult to machine, owing to their somewhat remarkable degree of work-hardening.

The effect of the pressure of the cutting edge of a tool upon these steels is to increase the surface hardness to such an extent that cutting becomes increasingly difficult or the tool breaks down.

By raising the sulphur content of the steel the metal becomes softer and more readily machinable, but at the expense of a loss in tensile strength and reduced corrosion resistance. The austenitic steels of this class may, however, be rendered much more machinable, without affecting their corrosion resistance and without any appreciable

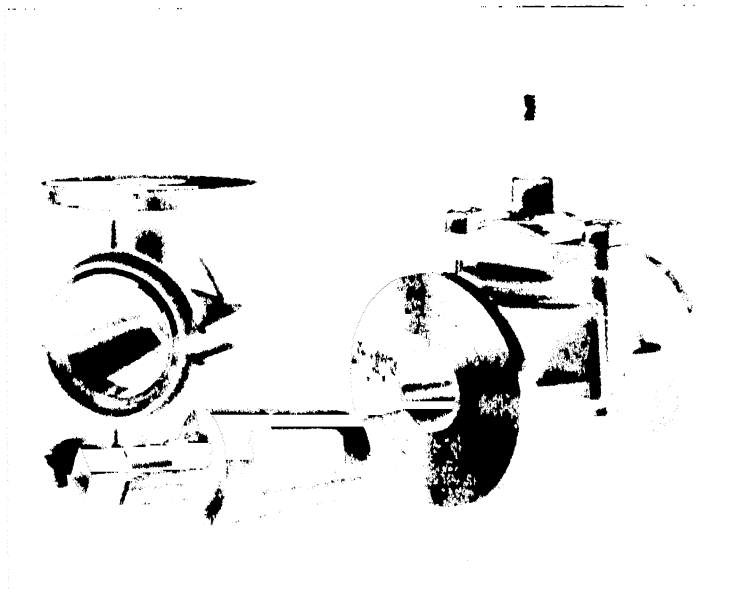


FIG. 120. EXAMPLES OF CHEMICAL VALVE CASTINGS IN FIRTH'S STAINLESS STEEL

reduction in strength, by the addition of a small percentage of *selenium*. Such steels have important possibilities for parts such as nuts, bolts, pins, and similar machined parts. For these purposes selenium-content stainless steels are supplied in bar form.

Corrosion Resistance of Staybrite Steel

Staybrite itself, in the polished state, completely resists atmospheric attack and is unaffected by marine conditions. It has a wide application range in the chemical industry and is resistant to a large number of chemical liquids, including the following acids: acetic, carbolic, benzoic, boric, citric, formic, lactic, malic, nitric, oxalic, phosphoric, "mixed" acids, picric, pyrogallie, stearic, sulphurous and

tartaric. It is attacked by hydrochloric, hydrofluoric, and sulphuric acids, and bromine, carbon tetrachloride, copper chloride, ferric chloride, and stannous chloride. It is, however, totally unaffected by petrol, benzole, paraffin, sea-water, acetone, fruit juices, vinegar, salt, photographic developers, and a very large number of chemical salt solutions; the makers publish a comprehensive list of the latter.

Aircraft Applications of Stainless Steels

Although employed as long ago as 1920 for aircraft structure parts, stainless steel was not more generally adopted until about 1930.

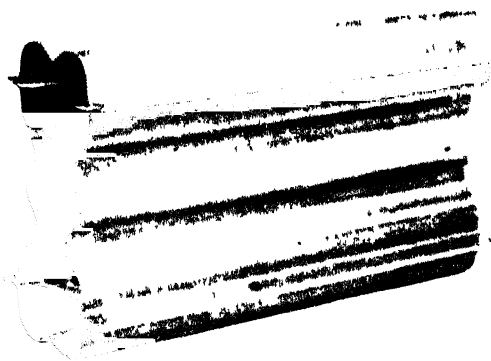


FIG. 121 AIRCRAFT WING SPAR MADE FROM FIRTH VICKERS' STAINLESS STEEL

To-day, extensive use is made of stainless steels in aircraft construction, notably for airframes and fittings exposed to atmospheric and sea-water corrosive action.

The steels employed for airframes, tubular members, such as fuselage longerons, and tail spars, undercarriage struts, etc., include those coming within the 12 per cent chromium steel group A,* and also the stainless iron class referred to later in this section. The tubes employed for aircraft purposes range in tensile strength from about 30 to 50 tons per sq. in. The group A steels used for plate fittings, in the form of sheets, include the 0.3 per cent carbon, 13 per cent chromium steels, of which Firth's F.G. is a typical example. This steel is subject to air-hardening after welding and certain precautions are necessary to avoid cracking; heat-treatment after welding is essential.

The group B (2 per cent nickel, 20 per cent chromium) steels, of which S.80 steel is typical, are used extensively for stampings and

* Vide page 242

in bar form for machined fittings for aircraft such as sockets, fork ends and pins, tube plug ends, eyebolts, wing roots, wing fixing lugs, undercarriage and engine mountings, turnbuckles, levers, nuts, bolts, studs and similar parts subject to high stress conditions. This steel, with minimum tensile strength of 55 tons per sq. in., is readily machinable but welding is not generally recommended.

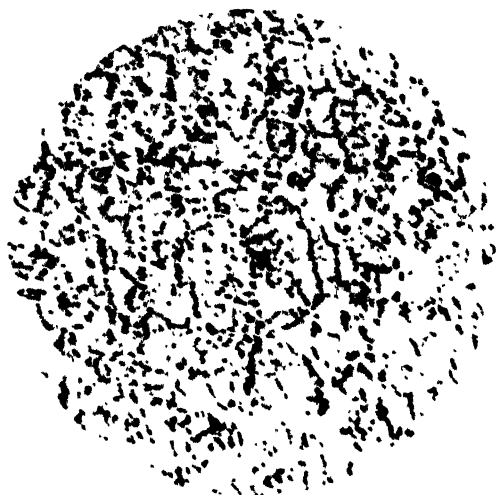


FIG. 122. STAINLESS IRON. $\times 500$

Stainless steel strip and sheet is widely used for low-stressed fittings. These include steel to the specification D.T.D. 171A for the softened condition steel used for plate fittings, seaplane float and flying-boat hull covering, monocoque fuselage and wing plating; in the cold-rolled condition steel to the D.T.D. specification 166A is employed for wing and tail spar, rib and strut construction, for junction plates, wiring lugs, etc.

In regard to *aircraft engines*, stainless steels are used for such items as pump spindles in liquid-cooled engines and control levers and rods of different types. A notable application of Staybrite F.D.P. steel is for exhaust manifolds and pipes in place of mild steel.

Stainless Irons

These include the high-chromium low-carbon metals containing up to 0.15 per cent of carbon and about 13 per cent of chromium, having a tensile strength of 30 to 40 tons per sq. in. and a higher ductility

than the higher carbon type of stainless steel; they also possess a rather greater resistance to corrosion attack.

Stainless iron is employed for turbine blading and for lightly stressed parts in the form of stampings, forgings, bar, plate, strip, and tubes in aircraft construction; also for golf-club heads.

The stainless irons are responsive to heat treatment and a wide variation in their physical properties is possible by quenching and tempering at suitable temperatures.

The following is a typical percentage composition: C, 0.15 (max.); Si, 0.50 (max.); Ni, 1.0 (max.); Cr, 12.0 (min.)—the manganese, sulphur and phosphorus are very low.

The metal, when normally heat-treated, namely, by oil quenching at 950° C. and tempering at 725–760° C., gives a yield point of 15 to 25 tons per sq. in. and a tensile strength of 30 to 40 tons per sq. in., with 40 to 30 per cent elongation and a Brinell hardness of 140 to 180.

The effect of different heat treatment upon the properties of this stainless iron is shown by the results given in Table 64 for Firth's steel corresponding to British Standard Specification S.61.

TABLE 64
EFFECT OF HEAT TREATMENT ON PROPERTIES OF STAINLESS
IRON

	1½ in. dia. Bar				
	Air cooled 1000° C.	Oil quenched 1000° C.	O. Q. 1000° C. T. 500° C.	O. Q. 1000° C. T. 750° C.	Close Anneal 850° C.
Yield point, tons per sq. in.	58.0	77.0	69.0	24.5	16.9
Max. stress, tons per sq. in.	75.0	80.6	82.3	37.2	31.5
Elongation, per cent	8	2.5	16	33	37.5
Red. of area, per cent	15	6.5	50.5	7.5	76.5
Brinell hardness number	340	364	370	172	140
Izod impact, ft.-lb. .	12	5	4	98	100

The *maximum shear stress* is 25.1 tons per sq. in., with yield shear stress of 11.6 tons per sq. in. The angle of twist on $\frac{3}{8}$ in. diameter \times 1½ in. parallel shaft is 500°.

The *fatigue limit* for 10 million stress reversals without fracture is 15.5 tons per sq. in.

The *modulus of elasticity* is 13,400 tons per sq. in.

These results apply to the B.S.I. S.61 steel in the normal heat treated condition previously mentioned.

The *specific gravity* of this stainless iron is 7.73.

The *thermal conductivity* at 20° C. and 600° C. is 0.059 and 0.066 C.G.S. units respectively.

The *electrical resistivity* at 20° C. and 600° C. is 56 and 107 microhms per cm. cube respectively.

The *coefficient of linear expansion* from 20° to 500° C. is 120×10^{-7}

Stainless iron is magnetic but is not suitable for permanent magnets. The following are its magnetic properties—

B (Induction) for H = 400	μ max. (Max. Permeability)	Hc (Coercive Force)	B Rem (Remanence)
17,170	500	7½	6100

Heat-treatment of Stainless Iron. This material is hardened by quenching in water or oil or by air-hardening, according to the size and section of the part in question, at a temperature of 950° to 1000° C. This is followed by tempering at 650° to 750° C.

To soften stainless iron it is heated to 750° C. and cooled in air. the metal is readily machinable in the oil-hardened and tempered condition, however.

Machining of Stainless Steels

The machining of these steels should preferably be carried out with high-speed tool steels such as the 18 per cent tungsten class, using keen cutting edges and rigid mounting both of the tool and work. An important point to remember in mounting the work is that steels of the Staybrite class have about 50 per cent greater linear expansion than ordinary steels, so that allowance must be made for the expansion due to the heat generated during cutting operations; thus, when turning Staybrite steel between centres the back centre should be adjusted accordingly.

The martensitic and ferritic steels in groups A and B* of the 40 to 50 ton tensile condition are machined at speeds of 70 ft. per min. for work of 1 in. diameter, with a cut of ½ in. and feed of ¼ in. The cutting speed is reduced with increase of diameter. Thus, for 5 in.

* Vide page 242.

diameter work the proper cutting speed would be 35 ft. per min., with a cut of $\frac{1}{16}$ in. and feed of $\frac{1}{18}$ in. The forms of the tools* for roughing purposes are shown in Fig. 123. Type A is used for ordinary work and B for relatively deep cuts, using the side of the tool. The appropriate rake angles for tool A are 10° to 13° (front) and 7° to 13° (side). The front and side clearance angles are 5° to 10° and 5° to 8° respectively. The front and side rakes for tool B are 7° and 15° to 20°

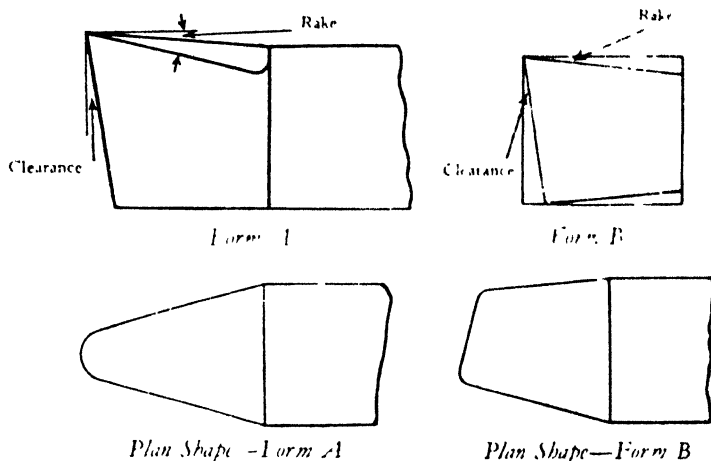


FIG. 123. FORMS OF TOOLS FOR TURNING STAINLESS STEELS

A—Ordinary tools B—Deep cuts

respectively, and the front and side clearance angles, 4° and 5° respectively.

Stainless iron cuts more cleanly than stainless steel. Higher speeds and keener rake angles with heavier cuts can therefore be employed.

The cutting speed for a 1 in. diameter bar is about 110 ft. per min., with $\frac{1}{8}$ in. cut and $\frac{1}{16}$ in. feed. The front and side rakes of the tool are 15° and 10° respectively. The front and side clearance angles are 5° in each case.

S.S.0 stainless steel machines in a similar manner to 3 per cent nickel or 3 per cent nickel-chromium steel. In the case of a $1\frac{1}{2}$ in. bar, a cutting speed of 100 ft. per min. is used, with $\frac{1}{16}$ in. cut and $\frac{1}{18}$ in. feed. The front and side rakes of the tool are 15° and 10° respectively; the front and side clearances are 5° in each case.

For finish turning stainless steels a light cut and higher speeds up to 100 ft. per min. (with 0.0025 in. cut and $\frac{1}{36}$ in. feed) should be

* Messrs. Thos. Firth & John Brown Ltd.

employed, using for this operation a broad-nosed tool with a cutting edge of $\frac{1}{4}$ in. to $\frac{3}{8}$ in. wide. The tool should be slightly rounded at the ends and have little or no side rake.

For finishing stainless iron a cutting speed of 150 ft. per min. can be used, with a cut of 0.003 in. and feed of $\frac{1}{4}$ in.

For drilling stainless steels of the group A and B class, high-speed steel drills should be employed with clearance angles of 8° to 10° ; for stainless iron the corresponding value is 12 to 15° ; for Staybrite steels 14 to 18° .

The drilling speeds for stainless and S.80 steels average about 50 ft. per min.; for stainless iron, 60 to 80 ft. per min., and for Staybrite steel, 30 to 35 ft. per min.

To ensure rigidity the drills should be as short as possible; small diameter drills should be gripped as low as possible in the drill chuck. Cutting lips should be ground with rather more back clearance and the point should be "thinned." Ordinary cutting lubricants can be used, but for fine work turpentine is recommended.

When *screw-cutting* stainless steels care is necessary to obtain a satisfactory finish, as there is some tendency to drag; a fairly high cutting speed may be employed, namely, 50 to 70 ft. per min. for 1 in. diameter work. The use of a cutting lubricant is not essential, but a light rub with tallow between the cuts is an advantage.

Higher speeds up to 150 ft. per min. can be used for *stainless iron* with a tool rake of 10° and clearance of 5° . For square threads a speed of 50 ft. per min. is recommended. For S.80 steel a speed of 80 to 90 ft. per min. gives good results with a top rake of 10° and 10° clearance.

Hack sawing should be done with high-speed steel blades at 100 to 120 ft. per min., using a copious flow of water or soluble oil. A 1 in. bar of stainless steel can be sawn through in $1\frac{3}{4}$ min.; a 4 in. bar in 25 to 30 min.

Cold sawing is recommended with segmented high-speed steel circular saws running at 30 ft. per min. with feeds of $\frac{1}{8}$ in. to $1\frac{1}{2}$ in., according to the section to be cut, for the group A and B steels. For Staybrite steels a rather lower speed, namely, 25 ft. per min., with $\frac{1}{2}$ in. to 1 in. feed, is desirable.

For *slab milling* stainless steels peripheral speeds of 40 to 60 ft. per min. are usually employed; for plain work a cutter with a quick spiral gives good results. For stainless iron, cutter speeds up to 80 ft. per min. can be used for general work, with a $\frac{1}{16}$ in. cut and a feed of $4\frac{1}{2}$ in. per min.

For S.89 steel a speed of 100 ft. per min. is advised, with $\frac{1}{4}$ in. cut and 5 in. per min. feed, using a double helical cutter and soluble oil lubricant.

Soldering and Brazing Stainless Steels

These steels can readily be soft-soldered, a suitable flux being made by dissolving into a 50 per cent solution of hydrochloric acid as much zinc chloride as the acid will take. Scrupulous cleanliness of the metal surfaces is necessary and care must be taken to ensure that the surfaces to be soldered are covered with flux. In other respects tinning and soldering are done in the normal way. It is important, however, to remove all traces of the soldering flux afterwards by washing in hot water.

Silver soldering necessitates thorough cleanliness of the surfaces. The best flux for stainless and Staybrite steels is one containing boracic acid and potassium fluoride; it can be obtained from one steel manufacturers. The flux may either be mixed into a thin paste with water or dropped on to the heated surface in powdered form. When using a low melting point silver solder the temperature should be about 700 °C.

Brazing of these steels is a more difficult matter, but if adequate protection of the surfaces to be brazed is given during the heating operation, a satisfactory result may be obtained. If the flux comes away from the surface of the steel during heating steel oxide will form, and the borax flux will not dissolve this oxide; the flux used should be a protective and not an oxidizing one; ground borax glass is preferable to borax as a flux. "Sifbronze" flux and wire or strip give very satisfactory results for brazing these steels.

Welding Stainless Steels

Stainless and Staybrite steels can be welded readily by all the usual electric and oxy-acetylene processes, but not by the smith's hearth method. Welding of these martensitic steels, however, tends to air-harden the metal in the vicinity of the weld so that it may be necessary to heat-treat the whole welded structure afterwards.

It is possible to electric arc weld light gauge stainless steel sheets as thin as 18 and 20 S.W.G. with modern welding plant.

When using the oxy-acetylene process it is *important to use a neutral flame*; otherwise the weld may be unsound. The gas pressure should be adjusted until correct fusion occurs. When welding thin sheets there is, however, a danger of piercing the metal if the pressures are too high.

The *welding rod* should always be of the same composition as the material being welded, and when welding sheets it is a safe rule to

use a gauge of rod or wire similar to or slightly heavier than the gauge of the sheet being welded.

When welding Staybrite steel the fact of the expansion being 50 per cent greater than that of mild steel must be allowed for. Another item to be taken into consideration is the lower thermal conductivity of Staybrite steel. Thus, when butt-welding steel sheets together the heat will not be conducted away through the sheets so rapidly as with mild steel and the hot zone will therefore be more confined. To allow for this the blowpipe flame should be played over a rather wider area than usual.

In some instances it is necessary to soften fully as well as descale Staybrite steel after welding, in order to obtain optimum corrosion resistance. On the other hand, other stainless steels do not need to be heat-treated after welding from this point of view, although it may be advisable to heat-treat after cold manipulation with a view to removal of stresses.

Although it is possible to weld stainless iron, welding results in embrittlement of the material adjacent to the weld, which is not wholly removable by heat-treatment. For this reason the welding of this material is not to be recommended as a general practice. The other martensitic stainless steels also air-harden when cooled from the welding temperature, and it is therefore necessary to heat-treat after welding.

Weld Decay of Stainless Steels. A type of intergranular corrosion experienced under certain conditions is due, basically, to the carbon content. In the case of chromium steels it produces a tendency to air-hardening and brittleness, but with stainless austenitic steels there is a grain-boundary precipitation of carbide which in certain circumstances results in intergranular corrosion.

When such steels are welded some of the metal in the region of the weld is heated to a temperature that causes the carbide to be precipitated again, so that these areas are liable to a type of corrosion known as *weld decay*.

In order to avoid such a tendency the carbon must be removed or absorbed into an inert condition such that it remains unaffected by heat-treatment.

The elements *tantalum* and *niobium* are employed for this purpose since they form stable compounds with the non-metallic elements and their carbides are not soluble in iron. Usually no more than 1 per cent of either element is satisfactory for this purpose, but the latter element—which has a much lower melting-point—is usually preferred. Niobium is also used in welding electrodes.

II. Heat-resisting Steels

Much modern engineering work demands steels that will retain a high percentage of their mechanical strength properties at elevated temperatures, and will resist corrosion or scaling tendencies.

The ordinary carbon steels quickly lose their strength when heated to temperatures of 500° C. to 700° C. Thus, in the case of ordinary structural mild steel the strengths at 500° C., 600° C., and 700° C. are respectively about 48, 30, and 17 per cent of the strength at ordinary atmospheric temperature. Moreover, mild steel when exposed to these higher temperatures in air begins to corrode very quickly.

Before the introduction of special heat-resistant alloy steels, it was the practice to protect the metal with a resistant coating, by calorizing and similar methods. Although to some extent successful in withstanding the corrosive effects of furnace gases and fumes, whilst the coating remained intact, the mechanical strength properties were impaired as previously shown, further, the coatings were liable to break down and expose the steel to corrosive influences.

A considerable amount of research has been done in connection with heat-resisting steels, and it is now possible to produce certain steels that will retain a fair amount of strength—namely, from 50 to 55 per cent at 600° C., and from 25 to 30 per cent at 900° C.—with almost complete immunity against corrosion.

Steels having in the cold state an austenitic structure and consisting of microscopically homogeneous grains are thus useful for high temperature work because, whilst this comparative uniformity is characteristic of most ferrous alloys at high temperatures, many of them develop a non-uniform, or heterogeneous, structure at the critical temperature which remains on cooling down, due to recrystallization and the separation of certain constituents. Alloys that do not possess a critical temperature, and therefore undergo no change on heating and cooling again, that is to say, solid solutions, are desirable for use at high temperatures.

The presence of free carbide, which in successful heat-resisting steels is very stable, does not appear to impair their heat-resisting qualities. The heat-treatment necessary for these solid solutions is comparatively simple, whilst the heating involved in such operations as brazing or welding has no effect upon them.

The serious weakening that occurs in the case of ordinary steels when they have attained a temperature of 500° C. to 600° C. is postponed in the case of heat-resisting steels, so that the latter will successfully withstand much higher temperatures—namely, from 600° C. to 1100° C., i.e. when the steel is from red to orange in heat colour.

Desirable High Temperature Properties

Steels that are subjected to elevated temperatures and stress effect should possess two distinct qualities, namely (1) resistance to oxidation and scaling, and (2) resistance to "creep" under steady and continuous loading at the higher temperatures, combined with a sufficiently high tensile strength value. The former property is possessed by steels containing an appreciable chromium content, i.e. above about 12 per cent and up to 30 per cent, and by chromium-nickel steels with relatively high chromium and nickel content -- up to about 30 per cent, with or without the addition of tungsten or titanium; these are austenitic steels.

Another type of heat resisting steel contains from 3 to 4 per cent of silicon and 6 to 10 per cent of chromium; it is known as silico-chrome steel and is one of the strongest of heat-resisting steels, giving a tensile strength of 65 to 70 tons per sq. in. at normal temperatures.

Yet another class of heat resisting alloy is one containing about 60 per cent of nickel and 20 per cent chromium.

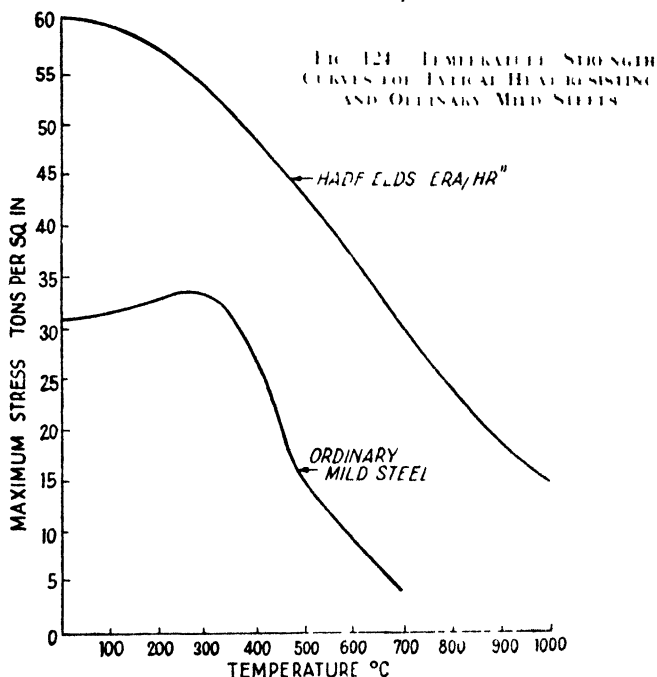
The resistance to creep in certain steels, e.g. nickel-chromium ones, is increased by the addition of tungsten up to 3 per cent.

Apart from the resistance to oxidation of a steel at elevated temperatures, it is also necessary in many instances for the steel to resist chemical attack by gases and vapours. Typical examples are the exhaust valves of internal combustion engines and certain parts used in industrial chemical processes. In order to afford a comparison of the resistances of steels to scaling or corrosion at high temperatures a method has been devised which depends upon the increase in weight, due to scaling, per unit area of surface per unit of time.

The Scaling Index is defined as the increase in weight, in milligrams, per sq. cm. of area of a specimen exposed for 24 hours in an atmosphere consisting of representative products of combustion. On this scale mild steel has a value, at 900° C., of 80, whilst a 13 per cent chromium steel, as used for automobile valves, furnace fittings, and chemical plant, subject to oxidation at a red heat, has an index of about 18. A 26 per cent chromium and 10 per cent nickel steel, with a tensile strength in the softened state of about 50 tons per sq. in. at normal temperatures, has a scaling index of about 0.2; this steel is used for case-hardening boxes, oil burners, and furnace muffles. Other heat-resisting steels with scaling indexes below 0.4 include Staybrite F.D.P., 30 per cent chromium steel (Firth-Vickers "Vesuvius"), 30 per cent chromium with 2 per cent nickel (Firth-Vickers "Pyrista"), and 60 per cent nickel with 20 per cent chromium (Firth-Vickers "Vikro") steel.

The effect of temperature increase upon the tensile strength of a

typical heat-resisting steel of the nickel-chromium series is illustrated in Fig 124. The results for mild steel over a temperature range of 0 to 700 °C are also given for the purposes of comparison. The Era H R steel at 700 °C has a tensile strength of about 30 tons per sq in, as compared with about 5 tons per sq in for the mild steel at 900 °C; the former steel has a tensile strength of about 19 tons per sq in, whereas that of the mild steel is a negligible quantity.



Some interesting results relating to the strength properties of this steel are given in the following table -

TABLE 65

TENSILE STRENGTH OF ERA H R STEEL AT VARIOUS TEMPERATURES

Temperature	Yield Point Tons per sq in	Maximum Stress Tons per sq in	Elongation per cent	Reduction of Area per cent
Normal	38	58.5	37.5	52
700 °C		31.0	35.0	57
800 °C		24.6	32.0	60
900 °C		19.0	30.5	64

Reference has previously been made to the resistance to creep of a steel exposed for appreciable periods to high temperatures. Creep stress tests are important as indicating the stress which the metal will resist continuously without failure, under given temperature conditions. In this connection it has been shown that the creep strength of the Era H.R. steel, previously mentioned, is no less than thirteen times that of the comparison carbon steel at 700° C.

The results are given in Table 66.

TABLE 66
CREEP STRESS FOR ERA H.R. AND CARBON STEELS

Material	Creep Stress (lb. per sq. in.)		
	500° C.	600° C.	700° C.
Era H.R. steel	42,500	38,000	26,000
0.30 per cent carbon steel	13,000	4,500	Less than 2,000

The resistance to scaling of the Era H.R. steel, together with comparative values for other steels, is given in Table 67.

TABLE 67
SCALING RESISTANCE OF STEELS AT 1000° C.

Steel	Loss in Weight (Grams per 100 sq. cm.)
Era H.R. steel	0.07
High chromium steel	7.31
High speed steel	7.40
Mild 0.16 carbon steel	28.40

The metals were exposed for 3 hours, with free access of air at 1000° C.

It will be observed that the scaling effect of the Era H.R. steel is practically negligible.

The steel in question is suitable for the rotors of exhaust gas turbines, such as those used for driving aircraft engine superchargers. These turbines operate at speeds up to 30,000 r.p.m. and are exposed to corrosive exhaust gases at temperatures of 700 to 900° C.; although running at a bright red heat, rotors of this metal are able to withstand

the high centrifugal stresses indefinitely. Other typical applications include Diesel engine valves, the racks of spring-hardening furnaces, and furnace conveyor members (Fig. 125).

The Time Yield Test. In connection with the creep strength of steels a convenient test which can be undertaken in a comparatively short period of time is one initiated at the Firth-Brown laboratories, known as the "Time Yield" test. The results obtained by this test

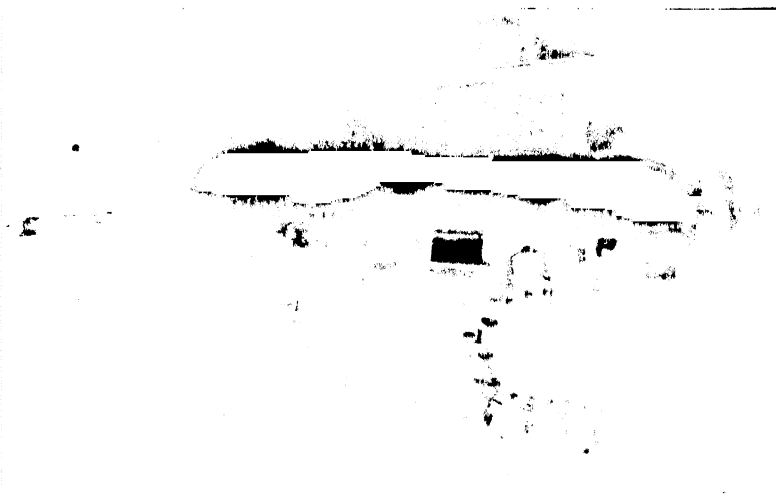


FIG. 125 FURNACE CONVEYORS MADE IN ERA H.R. STEEL

These have been in continuous service in a heat treatment furnace exposed to a minimum temperature of 950° C., without any signs of scaling.

afford a useful standard of comparison and this is employed for expressing the temperature-strength properties of heat-resisting steels.

The *time yield* is defined as the greatest stress, at any given temperature, which produces a rate of creep of no more than one millionth of an inch per inch per hour between the 24th and 72nd hours of test, the extension during the first 24 hours being less than 0.5 per cent of the gauge length. Typical time yield values for an austenitic heat-resisting steel at temperatures of 800°, 900°, and 1000° C. are, respectively, 1200, 280, and 90 lb. per sq. in.

From these results it will be appreciated how important is the selection of the correct operating temperature, for an error of 50° C. in estimating the temperature will cause a considerable variation in the stress value.

In the case of a good heat-resisting steel exposed to a temperature of 800° C., a permissible rate of creep of 10^{-8} in. per inch per hour would allow of the application of a load of only 500 lb. per sq. in. A rate of 10^{-7} would permit a load of 880 lb. per sq. in., 10^{-6} would permit 1600 lb., and a rate of 10^{-5} would permit a load of 3400 lb. per sq. in. From these few examples it will be apparent that the correct application of heat-resisting steel is a matter for careful study of the existing operating conditions.

Classification of Heat-resisting Steels

A convenient method of grouping these steels, due to Dr. Hatfield based upon their constituents and the proportions of these, is as follows:

A. Silicon-chromium steels.

B. Plain chromium steels (12-30 per cent chromium).

C. Austenitic chromium-nickel steels—chromium and nickel each up to 30 per cent, with or without additions of tungsten and titanium.

D. Higher nickel-chromium alloys, such as 60 per cent nickel and 20 per cent chromium, the rest being iron; this alloy cannot be termed a "steel," however, in the accepted sense of the word.

The percentage compositions of the principal elements and the mechanical properties of these heat-resisting steels and alloys are given in a convenient form in Table 68.

In connection with the steels and alloys given in Table 68, the following notes on their properties and applications may be found useful:

Group A steels possess excellent resistance to oxidation up to a temperature of about 900° C., but have no great mechanical strength at high temperatures. These steels are essentially used for internal combustion engine valves.

The first steel in *Group B* is very good for resisting oxidation up to about 700° to 750° C., but again possesses no special strength at high temperatures, although better than mild steel in this respect.

The second steel in *Group B* is excellent for resistance to oxidation up to about 1100° C. This steel has a tendency to be brittle at ordinary temperatures, although it is quite ductile at elevated temperatures. Again, this steel possesses no special mechanical strength at elevated temperatures.

In *Group C*, all the steels possess excellent ductility at ordinary temperatures and at elevated temperatures; all possess very appreciable mechanical strength, as compared with the previous steels. The

TABLE 68

COMPOSITIONS AND MECHANICAL PROPERTIES OF HEAT-RESISTING STEELS AND ALLOYS (W. H. Hatfield)

Typical Analysis					Mechanical Properties					
C	Cr	Ni	W	Mo	Condition	Yield Point lbs per sq in	Max Stress Tens per sq in	Elongation percent 2 in	Red Area percent	Brinell Hardness
<hr/>										
GHROL P A 0.4-0.5	6.0-10.0			3.0-4.0	Hot rolled and tempered	4-50	65-70	15-20	55-65	250-285
<hr/>										
GHROL P B 0.1-0.5	12.0-14.0				Hot rolled and tempered	15-40	30-60	20-40	40-60	140-280
0.10-0.20	25.0-30.0	0-5.0		1.0-2.0		20-35	30-45	1-2	30-50	150-225
<hr/>										
GHROL P C										
0.5 max	10.0-15.0	10.0-15.0	2.0-3.0	1.0-2.0	As furnished	30-40	50-60	20-35	30-50	220-290
0.5 max	12.0-16.0	25.0-35.0	0.4-0.5	1.0-2.0	As furnished	30-40	50-60	20-30	40-50	180-270
0.15 max	18.0	8.0	0.5-1.0	0-1.0	As furnished	16-20	40-60	35-50	40-50	160-200
0.2-0.4	19.0-26.0	7.0-13.0	0.4-0.5	1.0-2.0	As furnished	22-30	40-60	20-35	35-55	190-260
0.40 max	20.0-25.0	20.0-25.0		1.0-2.0	As furnished	22-30	40-55	30-50	40-60	180-260
<hr/>										
GHROL P D 1.0 max	15.0-25.0	60.0-80.0	0.4-0.5	1.0	As furnished	35-45	60-70	15-20	25-35	190-250

first two steels in this group show good resistance to oxidation up to about 900° C., whilst the third steel is very good up to 800° C., and the fourth and fifth steels are very good up to about 1050° to 1100° C.

The nickel-chromium alloy in *Group D* exhibits good resistance to oxidation up to about 1150° C., combined with good mechanical properties at elevated temperatures.

The physical properties of the steels given in Table 68 are set out in Table 69.

TABLE 69
PHYSICAL PROPERTIES OF HEAT-RESISTING STEELS
(W. H. Hatfield)

Group	Specific Gravity	Coefficient of Thermal Expansion 20 100	Thermal Conductivity (C.G.S. Units)	Electrical Resistivity Microhms per cm ²
A	7.60	0.0000130	0.030	75-85
B	7.74	0.0000106	0.045	52-65
	7.50-7.90	0.0000104	0.030	80-86
C	8.00	0.0000169	0.033	78
	8.00	0.0000151	0.030	85
	7.90	0.0000168	0.030-0.035	73
	7.80-7.90	0.0000155	0.030	85-87
	7.90	0.0000154	0.030	92
D	8.10	0.0000121	0.020	105

Typical Applications

Group A Steels These silicon-chromium steels are used chiefly for the exhaust valves of motor car, high-speed Diesel, and commercial petrol engines.

Group B Steels 1° (Cr. 12-14 per cent). For parts subject to scaling influence but not to very high stresses at temperatures up to 700° to 750° C. Typical instances are automobile engine valves, furnace, oil refinery, and boiler fittings.

2° (Cr. 25-30 per cent, Ni. 0.5-0 per cent): Medium-tensile steel properties in normal heat-treated condition, but is comparatively brittle at ordinary temperatures, being similar to highest-grade cast irons. Develops considerable ductility at elevated temperatures and excellent resistance to scaling at 1100° to 1150° C., but is

free from "growth" effects of cast irons with repeated heatings and coolings. Is employed in the form of bars, forgings, and castings for such parts as furnace fittings, mechanical stoker parts, roasting furnace rabble arms, and other parts not subject to appreciable loading or shock at ordinary temperatures. A typical commercial steel of this class is Firth-Vickers "Pyrista".

Group C Steels—1 (Cr, 10-15 per cent; Ni, 10-15 per cent; W,

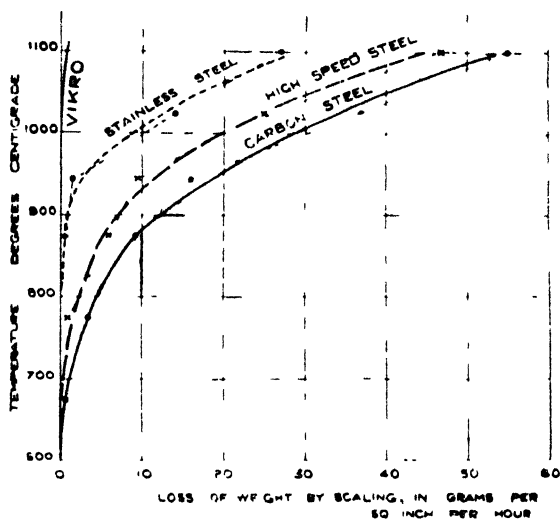


FIG. 126. RESULTS OF SCALING TESTS AT HIGH TEMPERATURES FOR VIKRO AND OTHER STEELS.

2-3 per cent). This austenitic steel has excellent oxidation resistance and a high creep strength. It is used chiefly for aircraft and automobile engine exhaust valves. Typical examples of this steel are the D.T.D. 49B Specification for aircraft engine valves and Firth-Vickers "Immaculate 9".

2. *High nickel-chromium steel* (Ni, 25-35 per cent; Cr, 10-25 per cent), with or without small additions of tungsten. Is used chiefly for turbine blading. Typical examples are D.T.D. 316 Specification (sheets and strip) and Firth-Vickers "Macloy B."

3. *Chromium-nickel-tungsten* (Cr, 17.0 (min.) per cent; Ni, 6-10 per cent; W, 2-4 per cent). Is employed in the form of bars, forgings, and castings for parts requiring high resistance to scaling combined with high strength at temperatures up to 1050° C. It possesses a very high creep strength at elevated temperatures and is used for

superheater supports, valve steels, etc. Typical examples are D.T.I. Specification 282 and Firth-Vickers "Immaculate 4W."

Group D Alloys. A typical nickel-chromium alloy (Ni, 60-80 per cent; Cr, 15-25 per cent) possesses excellent oxidation resistance at temperatures up to 1150 C., and has good mechanical strength properties at elevated temperatures. It is employed chiefly in the form of cast heat-treatment boxes which have to withstand the effects of high temperatures and bad handling. A typical example is Firth-Vickers "Vikro" alloy.

The resistance to scaling of this alloy is illustrated by the results of tests given in Table 70 for a number of machined cylinders, each of $\frac{1}{2}$ in. diameter by 2 in. long, of Vikro, and four other steels which were subjected to the oxidizing atmosphere of a furnace for a period of 100 hours at the temperatures mentioned in the table.

TABLE 70
SCALING TESTS OF STEELS AT HIGH TEMPERATURES

Temperature	Loss by Oxidation in grams per sq. in. per hour					
	675 C.	775 C.	875 C.	945 C.	1025 C.	1100 C.
Carbon steel	0.0080	0.0360	0.0940	0.1600	0.370	0.550
Nickel chrome steel	0.0095	0.0250	0.0700	0.1300	0.320	0.600
High-speed steel	0.0038	0.0100	0.0600	0.0950	0.250	0.470
Stainless steel	0.0005	0.0020	0.0080	0.0170	0.140	0.270
Vikro	Nil	Nil	0.0010	0.0014	0.002	0.008

In regard to the mechanical strength properties of Vikro steel, Fig. 127 illustrates the comparative tensile load values, at ordinary rates of loading, each of the specimens being first raised to the required temperature in a special tubular electric furnace. The superiority of Vikro steel at temperatures above 400 C. is marked.

Fig. 128 shows the results of "creep" tensile tests made on four different steels, under a uniform load of $8\frac{1}{2}$ tons per sq. in.: the tests at the lower temperatures continued for some thousands of hours. The graphs show the length of time required before the test pieces would be stretched to the point of fracture.

It will be seen that a bar of Vikro would endure a load of 8.5 tons per sq. in. for 2000 hours at 650 C. before breaking, while under the same conditions carbon steel would fail in a few hours. The maximum temperature at which "creep," or continuous flow, under a load of

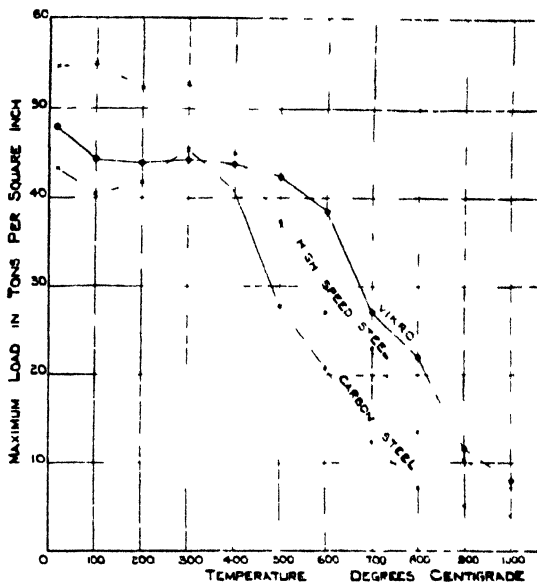


FIG. 127. TEMPERATURE STRENGTH CURVES FOR VIKRO AND OTHER STEELS.

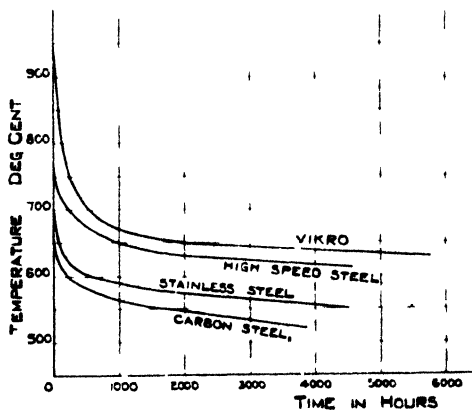


FIG. 128. CREEP TEST RESULTS FOR VIKRO AND OTHER STEELS.

8.5 tons per sq. in. is negligible, is shown to be about 625° C. in the case of Vikro, and only just over 500° C. in carbon steel.

III. High-manganese Steel

Steel having a relatively high carbon content, namely, from 1.0 to 1.4 with from 10 to 14 per cent manganese, possesses important physical and mechanical properties. This steel was discovered by Sir Robert Hadfield in 1882, and has since found increasing application in the form of castings, forgings and rolled products ranging from a few ounces in weight to several tons.

The important properties of this austenitic steel are that it is non-magnetic and when suitably heat-treated combines extreme toughness with high abrasion resistance.

The usual range of percentage compositions is as follows: C, 1.00 to 1.40; Mn, 10.00 to 16.00; Si, 0.25 to 1.00; P, 0.10 (max.); S, 0.05 (max.) As these variations can produce steels of maximum toughness but with different mechanical properties, it is necessary to narrow down the composition limits. In this connection the following analysis range covers the Imperial* manganese steels: C, 1.0 to 1.30; Mn, 12.0 to 14.0; Si, 0.20 to 0.40; P, 0.10 (max.); S, 0.05 (max.).

In the normal cast condition the metal is composed of austenite and free carbides. The austenite is a solution of iron, manganese, and carbides of these two elements. The carbides not in solution are very hard and brittle, and when present at the grain boundaries of the austenite, make the casting likewise brittle. A furnace soaking of the steel at about 1010° C. causes the austenite to absorb the free carbides into a solid solution, which can be maintained at room temperature by rapid quenching in cold water. However, if the metal section is too thick or the carbon content too high some carbide precipitation may occur during the cooling period.

The austenitic manganese steel is practically non-magnetic, having a permeability of less than 2.0, so that it has special applications for parts that have to combine non-magnetism with high strength and resistance to wear.

The initial hardness of manganese steel is about 185 to 200 Brinell, i.e. about the same degree as cast steel (unhardened), but under repeated impact or other work-hardening influences *the surface hardness increases* considerably, reaching at the point of embrittlement about 550 Brinell; this surface hardness is continuously renewed as the service continues.

In the "as-cast" state manganese steel is as brittle as cast iron,

* Edgar Allen Ltd., Sheffield.

but after heating and quenching at 1000 to 1050 C it possesses a *greater toughness than any other steel* in this steel the austenite is very strong and ductile these two properties contributing to its toughness

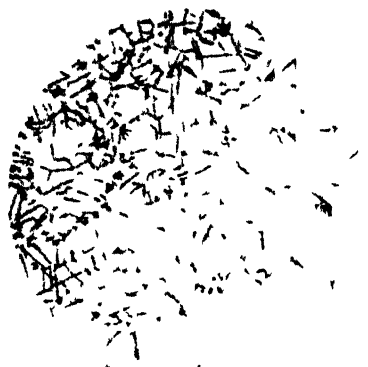


FIG. 129. MANGANESE STEEL TEMPERED
AT 1000 C. FOR 2 HOURS 66
(F. Edgar Allen Ltd.)



FIG. 130. MANGANESE STEEL BAR
WATER QUENCHED 66
(F. Edgar Allen Ltd.)

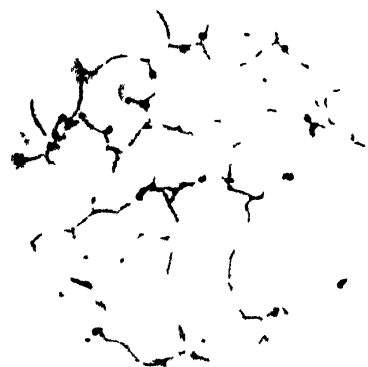


FIG. 131. MANGANESE STEEL,
AS CAST 33
(F. Edgar Allen Ltd.)

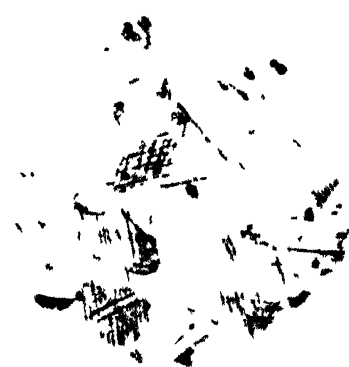


FIG. 132. MANGANESE STEEL WORK
HARDENED 66
(F. Edgar Allen Ltd.)

The uniform austenitic structure resulting from quenching at the correct temperature is *not stable* although returned at atmospheric temperatures. Moderate heating however will cause a re-precipitation of the carbides present in the cast metal with a consequent refinement of the structure.

Heat treated cast manganese steel in bar form is so ductile that it can be bent double when cold without fracture. Similarly castings of this metal will deform before fracturing. This deformation however is not continuous owing to the fact that cold working raises the yield point in the stressed areas.

Mechanical and Physical Properties

Manganese steel possesses high impact strength and ductility. It has however low thermal and electrical conductivity but a high coefficient of thermal expansion.

The principal properties of standard manganese steel* are as follows —

Specific gravity	7.92
Weight per cubic inch	0.286 lb
Melting point	1343 °C
Electrical resistance (Copper 1.7241)	70.0
Thermal conductivity (Copper 100)	2.31
Specific heat room temperature	0.145
Coefficient of expansion	0.000010 per °F
Ultimate strength	135,000 tons per sq. in.
Yield strength	135,000 tons per sq. in.
Elongation	45.0 % in 2 in.
Reduction of area	30.0 %
Brinell hardness (with out cold working)	185-200

The high ductility of the metal enables it to flow or deform readily under impact but the flow sets and the metal as previously mentioned hardens under repeated blows.

It is for these reasons that manganese steel possesses great wear resistance and is difficult to machine.

In regard to the toughness as indicated by the combination of strength and ductility of manganese steel the remarkable toughness is indicated by the results of tests involving the determination of the work factor i.e. the number of foot pounds of energy required to break the specimens. The results of tests on manganese steel and a heat treated alloy steel of similar tensile strength are shown as follows —

TABLE 71
COMPARISON OF TOUGHNESS AND ABRASION PROPERTIES OF
ALLOY AND MANGANESE STEELS

Steel	Tensile Strength Tons per sq. in.	Elongation per cent	Surface Hardness Brinell	Abrasion Factor	Work Factor Ft. lb. per cub. in.
Alloy steel cast (heat treated)	55.8	15	275	110	1550
Manganese steel	55.8	45	550	150	3640

* Edgar Allen Ltd., Sheffield

These results show that the work factor for standard manganese steel is over twice that of the commercial type of alloy cast steel. Another method of indicating the superiority of manganese steel is to compare the amount of energy required to fracture it in tension with that of other typical steels. If the tensile strength is multiplied by the percentage elongation at fracture for specimens of similar size, the product gives an approximate measure of the energy required to fracture. This product is known as the "*Merit Number*". The values given in Table 72 represent the merit numbers of some typical steels.

TABLE 72
MERIT NUMBERS OF STEELS AND IRON

Metal	Tensile Strength Lb. per sq. in.	Elongation per cent	Merit Number
Manganese steel	140,000	50	7,000,000
Nickel steel (heat treated)	207,000	14	2,898,000
Mild steel	60,000	30	1,800,000
Tool steel	130,000	5	650,000
Cast iron	20,000	0.5	10,000

The abrasion resistances of a number of steels and cast irons are given in Table 73. The figures shown are such that the higher the number the lower is the loss of weight by abrasion in a standard abrasion testing machine using wet silica sand.

TABLE 73
ABRASION TEST RESULTS

Standard manganese steel (not work hardened)	100
White cast iron (BHN 420)	115-123
Rail steel as rolled (BHN 285)	135
Chromium-nickel white cast iron (BHN 525)	139
Typical medium priced hard surfacing weld metal	77-133
Rail steel, heat treated (BHN 400)	147
Standard manganese steel (work hardened to 330 BHN)	147
Chromium-molybdenum white cast iron (BHN 550-615)	151-164
Economy hard-facing weld metal	133-173
Ni-Hard cast iron (550-650 BHN)	166-250
No. 459 hard-facing weld metal, torch welded (Min. 500 BHN)	250-330

The figures in brackets (BHN) denote the Brinell hardness numbers.

It will be observed that work-hardened manganese steel has a high abrasion resistance; its best performance, however, is given where both impact and abrasion action have to be withstood.

Notes on Manganese Steels

Manganese steel can be forged but special care is necessary to avoid de-grading the metal. After forging the steel should be heat treated by raising it to a temperature of 1010°C . and quenching in water.

Manganese steel is weldable, a nickel-manganese welding rod being employed; for repairing fractures an alternative is an 18/8 stainless steel rod. Care is necessary in welding to avoid overheating, as this tends to cause de-grading of the metal.

Manganese steel is only machinable with difficulty owing to its high work-hardening property. It can, however, be cut with certain alloy tool steels such as Edgar Allen Stag Major or Firth's Speedicut Six Leda, or tungsten-carbide tipped tools; ordinary tool steels are unsatisfactory and quickly become blunt. Where possible surplus metal should be removed by grinding. Holes can be drilled in manganese steel using super high-speed steel drills; hot punching is another alternative. Low cutting speeds of about 10 to 15 ft. per min. should be used. Manganese steel should not be used where the temperature exceeds about 340°C . With 3 to 5 per cent nickel and less than normal carbon content a cast nickel-manganese steel can be used safely at temperatures up to 595°C .

For castings of heavy sections the carbon content of manganese steel should be less than for thin sections since there is greater carbide precipitation from austenite during the slower cooling of thicker sections when quenched.

Manganese steel castings, made in moulds of dry, green sand or in some cases of metal, are employed for special purposes such as the parts of stone and ore crushing, grinding and dredging plant.

The casting procedure necessitates special care, as there is a tendency to crack or distort, owing to the high coefficient of expansion of the metal, or, in other words, its high shrinkage property. The metal requires large sink-heads to feed it as it tends to cool and contract.

Castings should be uniform in section throughout, and sudden changes of section avoided; bosses and heavy fillets should therefore not be employed.

Castings may be improved considerably by heating them almost to whiteness and then quenching in water; the effect is to increase both the strength and the ductility.

Manganese steel has a high coefficient of linear expansion, so that in making patterns for castings an allowance, namely, about $\frac{1}{16}$ in. per foot, should be made.

Manganese-chromium steel is a modern variation of the original

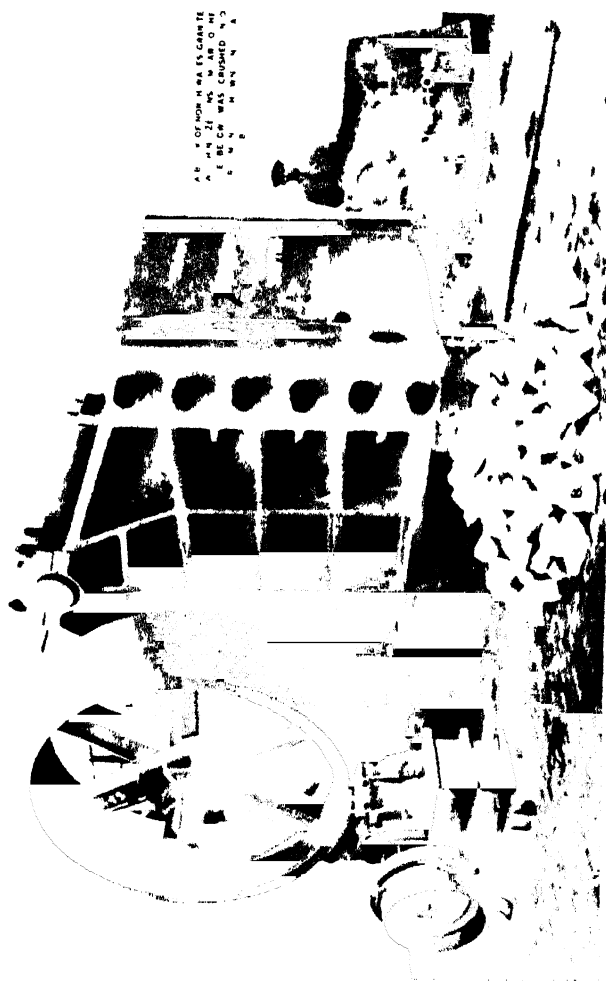


FIG. 13. A IARC(ORF) (RUSHER FITTED) WITH MAX AND STRENGTH. The vertical axis is 100 fold and decreases with distance from the

12 per cent manganese steel. A typical percentage composition, conforming to D.T.D. 9B Specification is as follows: C, 1.0 to 1.5; Si 0.5 (max.); Mn, 11.0 to 14.0; Cr, 1.40 (max.). It is forged at 1150° C. down to 900° C., and is water-toughened at 950° C. to 1150° C.

Manganese-nickel steel. By the addition of 3.0 to 5.0 per cent nickel to the standard manganese steel formula and a reduction of the carbon content it becomes possible to retain an austenitic structure in thin sections without quenching and with only a normalizing treatment. Also, in the case of abnormally thick sections a nickel addition retards phase transformation during quenching. Nickel-manganese steel castings in use are less susceptible to de-gradation from welding heat or operating heat than the standard. The cost per pound of steel is higher, however.

Applications of Manganese Steels

The marked property of work-hardening renders this steel eminently suitable for such parts as the jaws of stone and ore crushers, dredger parts, tramway and railway points and crossings, etc.

In the former application the crusher jaws of manganese steel are less durable when dealing with sharp friable material than when crushing refractory material, since in the latter case the maximum hardness in the working surfaces of the jaws is developed. For this reason, also, manganese steel parts are difficult to machine as the cutting tool tends to work-harden the metal under the cutting edge, whereas the cutting action of a suitable abrasive wheel removes the metal in the form of minute chips without abnormal hardening.

Manganese steel has been much used for shrapnel-proof helmets and shields; it is also a good material for "burglar-proof" safes and vaults as it is too hard to be cut with ordinary tools and too strong to be broken away with ordinary explosives.

Manganese steel in the hot-worked condition is much used for rails. The latter are rolled in ordinary rail-rolling mills and are heat-treated by quenching soon after rolling; the material then has a yellowish tint due to *austenite*; this feature differentiates it from ordinary carbon steel.

Manganese steel in the form of bars is now widely used for screening coke. Ordinary steel wears away rapidly under the impact of the coke, but with manganese steel it has a life about a hundred times as long.

This steel is also used for slow speed railway truck wheels for mines and factories, but is not suitable for high speed wheels.

Owing to its *non-magnetic property*, it has an important use in the

cover-plates of lifting magnets for handling heavy iron and steel articles, and also for ship structures situated near the magnetic compass, since it has no magnetic effect on the latter.

Other applications include grinding and dredging plant parts and agricultural implements, such as shovels and hoes; these are made from rolled manganese steel plates.

IV. High-speed Tool Steels

When carbon tool steels are employed for machining purposes there is a definite limit to the cutting speeds and feeds that can be employed, and therefore to the rate of production. With the adoption of mass-production methods and the use of alloy steels for engineering purposes the demand arose for a more efficient tool steel that would give higher cutting speeds under heavier loads.

The carbon steels, generally speaking, do not retain their edges under the heavier loads and higher speeds, for the heat developed causes a loss of temper and the tools will no longer cut efficiently. What was wanted, therefore, was a tool steel that would keep its temper hardness even when heated during machining operations, and would enable heavier and quicker cuts to be taken.

The solution was sought in the alloy steels, the earliest example being the tungsten steel, introduced by Mushet about 1860. This steel was a high carbon one (2 per cent), with from 4 to 6 per cent of tungsten. The silicon averaged about 1 per cent, and the manganese from 1 to 1.5 per cent. This steel was self hardening, and possessed very much better cutting properties than the carbon steels.

Another tungsten steel, introduced in America about 1894 by Messrs. Taylor and White, was an advance upon Mushet steel, from the point of view of performance. It contained 8 per cent of tungsten, and 3.8 per cent of chromium. This steel is to some extent similar to the modern high-speed steels in composition.

The principal elements found in the composition of modern tool steels include tungsten, chromium, vanadium, cobalt, and molybdenum. Not all of these are normally present, but usually two or three.

Of these elements, tungsten is probably the most important and in most of the modern high-speed steels it is alloyed in proportions of 14 to 22 per cent. In addition chromium and vanadium are present, whilst in the higher grades cobalt and molybdenum are also employed.

It is possible to use a variety of combinations of these elements, but most manufacturers of these steels have standardized their own limited ranges of steels with these elements.

The principal advantage of steels such as the high tungsten ones

is that they will retain their cutting hardnesses up to temperatures approaching a red heat, whereas carbon steels would quickly become "soft" under the same conditions. This point is well illustrated in the case of tests made at the Firth Laboratories on turning tools of identical design which were put to work on an 8 in. diameter bar of 0.90 per cent carbon steel, which had a tensile strength of 60/65 tons per sq. in.—thus affording a somewhat severe machining material. Two tools were used, namely, a high grade carbon and a 14 per cent tungsten "Speedicut" alloy steel. The initial cutting speed was 30 ft. per min. with a $\frac{1}{8}$ in. cut and feed of $\frac{1}{16}$ in. per revolution. The speed was increased by 1 ft. per min. every minute. Under these conditions the Speedicut tool ran efficiently for a period of between 16 and 17 minutes, attaining a cutting speed of 46 ft. per min., whereas the carbon steel tool failed as soon as it was put to work.

Cutting Speeds

The cutting speeds of tool steels depend upon a number of factors, the principal ones of which include (1) the design of the tool, i.e. whether for roughing, finishing, parting, side-cutting, etc.; (2) the nature of

TABLE 74
CUTTING SPEEDS AND FEEDS FOR TURNING TOOLS

Depth of Cut in Inches	Feed in Inches	Cutting Speeds for Steels in Feet per min.			Depth of Cut in Inches	Feed in Inches	Cutting Speeds for Cast Iron in Feet per min.		
		Soft Steel	Medium Steel	Hard Steel			Soft Cast Iron	Medium Cast Iron	Hard Cast Iron
$\frac{1}{32}$	$\frac{1}{64}$	476	238	108	$\frac{1}{8}$	$\frac{1}{16}$	122	61	36
	$\frac{1}{32}$	325	162	74		$\frac{1}{8}$	86	43	25
	$\frac{3}{64}$	177	88	40		$\frac{3}{16}$	70	35	21
$\frac{1}{16}$	$\frac{1}{32}$	240	120	55	$\frac{1}{4}$	$\frac{1}{16}$	99	50	29
	$\frac{3}{64}$	164	82	37		$\frac{1}{8}$	70	35	20
	$\frac{1}{16}$	112	56	26		$\frac{3}{16}$	57	28	17
$\frac{1}{8}$	$\frac{1}{32}$	213	107	48	$\frac{3}{8}$	$\frac{1}{16}$	91	45	26
	$\frac{3}{64}$	116	58	26		$\frac{3}{16}$	52	26	15
$\frac{1}{4}$	$\frac{1}{16}$	180	90	41	1	$\frac{1}{8}$	80	40	23
	$\frac{3}{32}$	122	61	28		$\frac{1}{4}$	56	28	17
$\frac{3}{8}$	$\frac{1}{8}$	237	118	54	$1\frac{1}{2}$	$\frac{3}{16}$	75	38	22
	$\frac{3}{16}$	162	81	37		$\frac{1}{2}$	43	22	13

[Machinery Handbook]

the metal to be cut, i.e. the metal and its heat-treatment; (3) the depth of cut, and (4) the rate of feed of the tool.

It is possible to employ a range of cutting speeds for the same material to be cut and with the same tool, steel, by varying the last two factors. Thus, for a given tool life, i.e. a given period of time before regrinding becomes necessary, cutting speeds ranging from 100 to 500 ft. per min. are employed in the case of a good grade high-speed steel, *used for machining mild steel* with various feeds and speeds. Table 74 shows the cutting speeds and feeds for a good grade of high-speed steel of $\frac{7}{8}$ in. square section, for a life between grinds of $1\frac{1}{2}$ hours.

The cutting speeds, under similar conditions of material hardness, feed and speed for tools made from high grade carbon steel, Mushet's self-hardening steel, Taylor White (1.85 C - 8.0 W, 3.8 Cr) steel and a modern high-speed, high tungsten steel are in the ratio of 1 : 1.6 : 3.7 : 6.5 respectively.

In connection with the use of high-tungsten content tool steels, it should be mentioned that whilst these will cut satisfactorily with their cutting edges at a dull red heat upon cooling down they still retain their cutting hardness.

Typical High-speed Steels

The tungsten steels now generally adopted for metal cutting tools may be grouped into two broad classes—namely those steels containing no cobalt and those with the latter element. The cobalt steels can be used at higher speeds, notably for rough machining, but are more brittle than the steels of the other class; incidentally, they are more expensive. The heat-treatment of these steels requires special care in order to prevent surface burning and loss of carbon content. These steels are often used for tools in which the shape is formed by grinding after hardening, e.g. for lathe and planer roughing and finishing tools and inserted blades for cutters, etc.

Cobalt steel tools with high tungsten content (18 to 22 per cent) are employed for machining hard chilled cast iron, high tensile alloys, hard railway tyres and heavy alloy steel forgings. One special grade of 20 per cent tungsten-cobalt steel with other elements is used for heavy duty purposes such as heavy cuts on high tensile steel forgings, for close-grained hard cast iron and for machining manganese steel; a typical cutting steel of this class is Firth's "Speedicut Six-Leda," which is used for machining steel of 100 tons per sq. in. tensile strength and 12 per cent austenitic manganese steel in production work.

Tungsten-chromium-vanadium steels are much used in the U.S.A. and also in this country for high-speed tools. These are known as the 18-4-1; 18-4-2; 18-4-3 and 14-4-2 types, and their percentage compositions are given in Table 75.

TABLE 75
COMPOSITIONS OF HIGH-SPEED CUTTING STEELS

Type	Carbon	Tungsten	Molybdenum	Chromium	Vanadium
18 4 1	0.70 0.75	18.0		4.0	1.0
18 4 2	0.80 0.85	18.0	0.75	4.0	2.0
18 4 3	0.85 1.10	18.0		4.0	3.0
14 4 2	0.80 0.85	14.0		4.0	2.0
Molybdenum	0.80 0.85		10.0	4.0	1.0

(Kent)

The compositions of typical cobalt high-speed cutting steels are given in the following table

TABLE 76
COMPOSITIONS OF COBALT HIGH-SPEED CUTTING STEELS

Type	Carbon	Tungsten	Molybdenum	Chromium	Vanadium	Cobalt
18 4 1 4% cobalt	0.70 0.75	18.0	0.5	4.0	1.0	4.0
18 4 2 7% cobalt	0.75 0.80	18.0	0.75	4.0	2.0	7.0
20 2½ 14 12% cobalt	0.80 0.85	20.0	1.00	2.5	1.5	12.0
14 4 2 4% cobalt	0.75 0.80	14.0	0.25	4.0	2.0	4.0

(Kent)

Tantalum and Niobium Tool Steels Tantalum and niobium are elements of specific gravities 16.6 and 8.57 respectively, with melting points of 2850 °C and 1950 °C, respectively, which impart special properties to carbon steels.

The principal effect of tantalum when added in small amounts to a carbon steel is to reduce the amount of iron carbide. In the case of 0.95 per cent carbon steel having 3 per cent of tantalum about one-half of the iron carbide normally present is removed. When this steel is heated to a suitable temperature and quenched, it is found that in addition to the uniform martensitic background there is a further constituent, namely, tantalum carbide (Fig. 134).*

A 1.2 per cent carbon steel having 18 per cent of tantalum has the whole of the carbon converted into the extremely hard tantalum carbide whilst the excess of tantalum is present in the form of an iron-tantalum (Fe_2Ta) compound. Fig. 135 shows a photomicrograph of this steel, the larger tantalum carbide particles are here clearly indicated.

* Courtesy of Iron and Steel Institute.

Tool steels containing the latter compound have excellent cutting properties. Usually these steels are made direct from pig iron with 2 to 4 per cent of carbon to which a certain amount of ferro tantalum

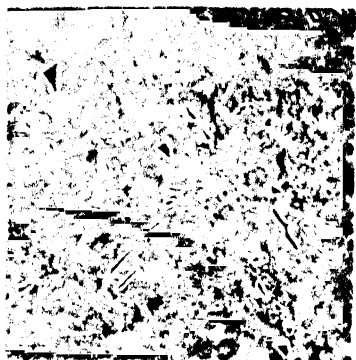


FIG. 134. 0.91 PERCENT CARBON, 10 PERCENT TANTALUM STEEL, HARDENED

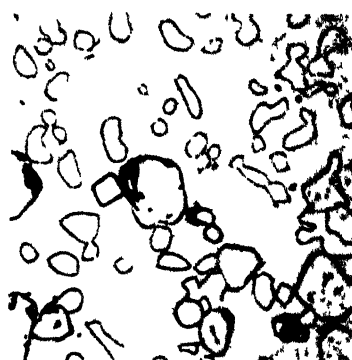


FIG. 135. 1.2 PERCENT CARBON, 18 PERCENT TANTALUM STEEL, HARDENED

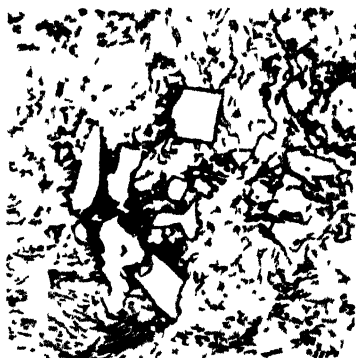


FIG. 136. TOOL STEEL MATRIX WITH TUNGSTEN AND TANTALUM CARBIDES

is added so that the whole of the carbon is converted into tantalum carbide, it is usual to add small amounts of tungsten and chromium to such steels. The structure of the alloy thus formed (Fig 136) consists of a tool steel matrix containing larger particles of extremely hard carbide. A typical cutting alloy known as *Tantung* consists of fine particles of tungsten and tantalum carbides embedded in a matrix

of chromium and cobalt, and it is distinguished from other carbide compositions by being *cast instead of sintered*. Whilst not quite so hard as other carbides, it is *much tougher* so that the edges of cutting tools will stand up to impacts and interrupted operations much better than the ordinary tungsten carbide tipped tools. For this reason *heavier cuts* can be taken, but at rather lower cutting speeds.

The fact that Tantung can be cast instead of having to be sintered enables various shapes to be obtained by welding; it can also be welded direct on to carbon steels.

The tantalum carbide tools also possess a marked resistance to the *cratering effects* associated with tungsten carbide tools; they are also self-lubricating.

Heat-treatment of Tool Steels

The heat-treatments of the various high-speed steels vary considerably and the manufacturers' directions should generally be sought in each case.

There are, however, *two important properties* of high-speed steel which are common. Firstly, the temperature at which the steel must be hardened, so as to give the maximum cutting efficiency, is higher than in the case of carbon tool steels. Thus, in the case of plain carbon steels or steels containing small percentages of tungsten and chromium, the quenching temperatures are normal, i.e. from just above the Ac. 3 point (usually from 700° C. to 800° C.), according to the particular composition employed. In the case of high-speed steels it is necessary to heat these to a much higher temperature—namely, a little short of fusion (from 1150° C. to 1350° C.)—to obtain the full advantages of these steels.

The second characteristic feature of high-speed steel is its marked *resistance to tempering*. Unlike carbon steel which tempers at definite temperatures, with its hardness decreasing gradually as the tempering temperature increases, from the initial reduction in hardness value at about 250° C., high-speed steels do not lose their initial hardness even when tempered, in some cases, at a temperature as high as 610° C. When the carbon content is high, the steel after tempering is actually harder than it is in the quenched condition.

It follows from the above facts that these high-speed steels can be used for tools that heat up by friction when machining to relatively high temperatures and that the tool will retain its temper indefinitely provided it is not heated above 580° C. to 610° C., the actual value depending upon the composition.

(It is important to remember that high-speed steel will only develop

its properties of red-hardness and resistance to tempering it has previously been hardened correctly.

As supplied, high-speed steels are generally *annealed* and can be filed or machined without difficulty. In the case of small pieces for tool-holders, however, the manufacturers generally supply the steel in the hardened state.

Although it is possible to render high-speed steel extremely hard by the process of quenching in oil or water from, say, 1000 °C. and thus to give it a high degree of hardness, the material would not possess the necessary resistance to tempering.

The correct methods of hardening high-speed steel are to some extent governed by the composition, but it is a general rule that high-speed steel should not be quenched in water—it should be cooled quickly in whale oil or by means of an air-blast.

The usual procedure with high-speed steel is to preheat the part in a muffle (gas or electric-heated, for preference) to a bright red heat (800 °C. to 870 °C.), and after a certain short period of "soaking" to transfer to another final heating furnace. In this the temperature is raised quickly to about 1200 °C. to 1300 °C., and the part quenched in oil or an air-blast.

The time of "soaking" plays an important part in the process of hardening, for if too long the steel will become over-hardened and brittle. If it has not soaked long enough, it will be too soft from the Brinell hardness point of view.

When *hardening cutting tools* of high-speed steel, the nose only is heated rapidly to 1200 °C. to 1300 °C., after the preheating period at the lower temperature.

Parts such as milling cutters, hobs, drills, and similar multiple cutting-edge tools must have their cutting-edges protected from corrosion or burning during the final heating process.

The salt-bath method is often employed. If the tools are heated in a furnace, they should be enclosed in a suitable receptacle, and may be covered with some kind of a silica paint as a further protection.

It is important to warm the steel parts before they are placed in the preheating furnace, and then to heat them *slowly* until the proper temperature is reached. The reason for this is that high-speed steel is denser and, therefore, requires a longer period of heating; if a cold bar of this steel is placed in a hot furnace, the outside would expand more quickly than the interior, causing severe internal stresses, resulting in the condition known as a "clink." Although the bar to the eye appears as before, and exhibits no flaws, yet when in use the

tool may break, the fractured surfaces showing the "cup and cone" appearance associated with incorrect heating procedure.

After hardening, the *tool steel should be tempered* at the temperature (580 °C to 610 °C) recommended for the particular composition. The manner in which the cutting hardness of a high grade tool steel varies with the tempering temperature is illustrated in Fig. 137 for

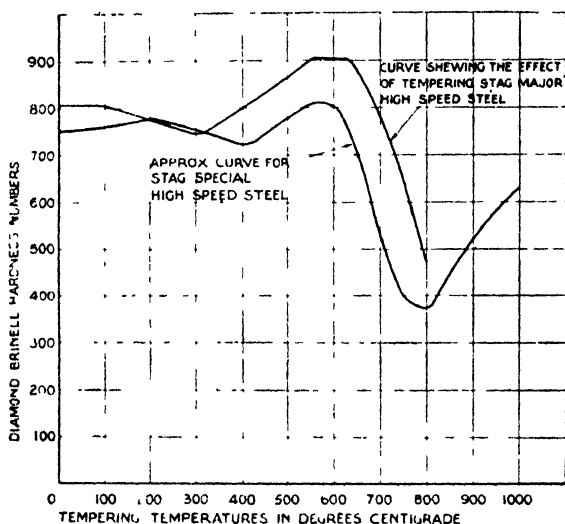


FIG. 137. EFFECT OF TEMPERING TEMPERATURE ON HARDNESS OF TOOL STEELS

two steels known as "Stag Major" and "Stag Special," made by Edgar Allen Ltd.

The relatively narrow temperature range of 580 °C. to 610 °C. for the attainment of the maximum hardness is shown by these curves.

For tempering tools made from such steels they should be loaded into a furnace or salt bath provided with accurate thermostatic control at 580 °C. to 610 °C. and, after soaking the nose of the tools (or in the case of milling cutters the whole of the tool) through, they should be held at this temperature for about half an hour and then allowed to cool in an oil bath or the open air. The end of the thermo-couple employed for measuring the furnace or salt bath temperature should be placed as close to the tool as possible.

Cemented Carbide Cutting Materials

Whilst considering the general subject of cutting materials it is convenient to include an account of the non-ferrous cemented carbide products employed for tipping steel tool shanks and other purposes. The principal element in these materials is tungsten, and the plain tungsten carbide is made by mixing tungsten and carbon in powdered

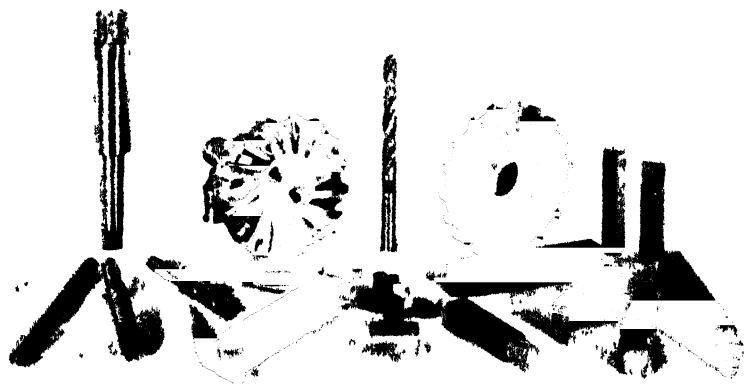


FIG. 138. EXAMPLES OF ARDOLLOY TIPPED TOOLS
(Alfred Herbert Ltd.)

form and heating in an electric furnace. The product itself has no special value, but when powdered and mixed with 3 to 20 per cent of powdered metallic cobalt and sintered at a temperature well below the melting point of tungsten carbide, namely 1000° C. in a hydrogen atmosphere, it forms a heavy brittle product which can be cut and filed to any desired shape. The final cutting material is obtained by heating this product to about 1500° C. for several hours in a hydrogen atmosphere with carbon. Cemented tungsten carbide is thus obtained with the cobalt acting as a cementing medium, but not in combination with the tungsten or carbon.

A good deal of shrinkage occurs during the final heating process so that in arranging for dimensioned parts an allowance of about 20 per cent shrinkage is made.

Tungsten carbide thus obtained has a specific gravity of 14 to 15. It is extremely hard and can only be formed to cutting tool shapes by grinding. Owing to the fact that it is an expensive material it is employed to tip carbon steel tools, milling cutters, drills and similar items.

The modern cemented carbides contain other elements such as molybdenum, titanium, tantalum, chromium, etc.

Typical commercial cemented carbides are *Wimet*, *Ardoloy*, *Carboloy*, *Cutanit*, etc. Other synthetic cutting materials include *Stellite* and boron-carbide.

Cemented carbides, as stated previously, are extremely hard; they have a hardness on the Moh scale of 9.2 to 9.7 and will scratch glass and also sapphire, they are thus harder than any heat-treated alloy

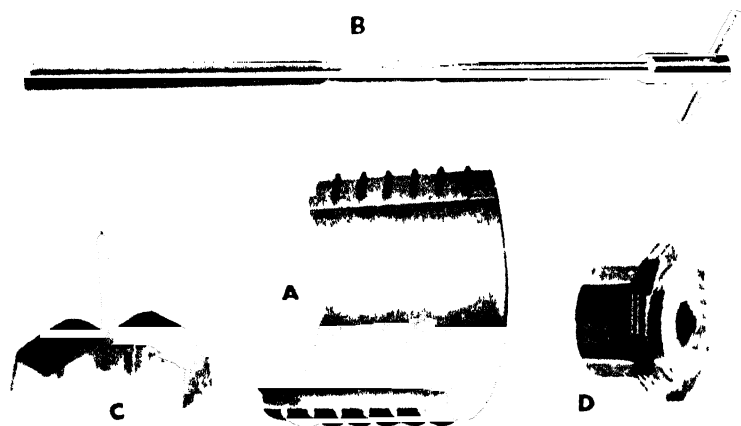


FIG. 139. EXAMPLES OF WIMET TIPPED TOOLS

- A Tool for cutting grooves in lead pencils
- B Reamers for small pump barrels
- C Punches and dies
- D Former hob for cutting synthetic material (Paxolin)

tool steel. At the same time these carbides are of low tensile strength and are therefore unsuitable for heavy tool pressures or use under impact or intermittent cutting conditions.

Their principal advantages lie in the extreme hardness of the cutting edges which enable them to be used at much higher cutting speeds than alloy tool steels, but with rather finer feeds. Owing to their high degree of abrasion resistance cemented carbide tipped tools can be used for long periods on materials such as whitemetal, fibre, ebonite, bakelite, etc., which are known to wear alloy tool steels at a relatively high rate. In common with some of the latter tool steels, cemented carbide ones will operate satisfactorily at temperatures up to those of red-hot steel without breakdown or alteration of their cutting properties. It is, however, essential that these tools are used on rigidly designed machines, free from vibrations in the work and

tool-holding fixtures or the framework of the machines; for this reason specially designed machines are necessary for use with tungsten-carbide tools.

Cemented carbide of the Carboloy class can now be *extruded* in the form of tubing, spirals, round and shaped bars in lengths up to 20 in., and within a diameter range of 0.015 in. to 0.375 in. Carboloy tubing can be made as small as 0.06 in. outside diameter and wall thickness of 0.015 in. Rods of this material can also be bent, by a special process, to various shapes, including that of a ring with the ends joined together.

In connection with the use of cemented carbide tips to steel tool shanks, this is usually effected by the method of copper brazing; the material should be well supported by the tool shank when brazed into position.

Normally cemented carbides are made in several grades for various purposes from light to heavy machining operations and standard tips with several rakes or cutting angles are provided by the manufacturers. Thus, in the case of Ardoloy,* seven different grades are available for standard tips in four tool rakes as follows: (1) Copper and aluminium, 24°; (2) mild steel, 16°; (3) steel castings, alloy steels and light cuts in cast iron, 8°; (4) manganese steel, gun-metal and phosphor-bronze and for roughing cuts of cast iron, 3½°.

The *cutting speeds* with cemented carbide-tipped tools are the highest used for any tool materials; they are from 2 to 3 times those of high-speed 18 per cent tungsten steel tools. In this connection cutting speeds up to 1000 ft. per min. are used for brass bar, aluminium and magnesium alloys, as against speeds of 250 to 400 ft. per min. for tungsten steel tools. Bakelite and ebonite are machined at speeds up to 700 ft. per min. and porcelain insulators at 10 to 20 ft. per min.

Free-cutting mild steel is machined at 300 to 600 ft. per min., whilst annealed alloy steels such as 3 per cent nickel steel and nickel chrome steels are cut at 200 to 350 ft. per min. Hard white cast-iron castings are machined at 100 to 120 ft. per min., grey cast-iron ones at 90 to 120, and malleable iron (annealed) at 200 to 300 ft. per min.

Other materials that are machinable with cemented carbide tools include mica insulation in electrical commutators, electrode carbon, marble, stone, ivory, compressed paper, rawhide and bakelite reinforced with linen. Cemented carbide is also used for wire-drawing dies, wearing surfaces of gauges, work rests, reamers, form tools, screwing tools, drills, milling cutters, etc.

* Alfred Herbert Ltd., Coventry.

The cutting speeds recommended for the cemented tungsten carbide known as Ardoloy are given in Table 77.

TABLE 77
CUTTING SPEEDS FOR ARDOLOY TIPPED TOOLS

Material	Cutting Speeds, Feet per Minute
Cast steel 40 90 tons tensile	80 200
Stainless steel -	
Bar	100 200
Castings	60 100
Chrome-nickel steel and other alloy steels 40 90 tons tensile	150-200
High-speed steel (annealed)	90-150
Manganese steel (12% manganese)	10 25
Cast iron	
200 Brinell	200 400
Close grained	150 250
10% nickel iron	20 30
Chilled iron rolls	8 20
High silicon iron	20 60
Pearlitic iron	15-30
Malleable iron	100-300
Copper	
Soft brass	As fast as machine will allow
Cupro nickel	350 500
Hard brass, phosphor bronze, manganese bronze, gun- metal, Admiralty bronze, etc.	750 1250
Aluminum	As fast as machine will allow
Aluminum alloys	300 750
Soft rubber	750 1000
Erinoid, ebonite, bakelite, hard rubber, fibre, etc.	500 800
Porcelain, marble	10 30
Slate	50 100
Glass	30 70

Stellite

This cutting material has been in active use over a long period. It consists of cobalt, chromium, tungsten and carbon, and the alloy contains the cast carbides of tungsten and chromium in a ground-work of chromium and cobalt. Unlike the high-speed tool steels Stellite is inherently hard and requires no heat-treatment.

Stellites may be regarded as cutting materials with properties intermediate between those of high-speed tool steel and the cemented carbides. They are nearly as hard, at room temperature, as the former, but softer than the latter, while above 550° C. they are harder than high-speed tool steel but not as hard as, though actually tougher than, the cemented carbides; the latter, however, retain their red or hot hardness better than other cutting materials.

The well-known *Grade 40 Stellite* contains 45 to 50 per cent cobalt, 30 to 35 per cent chromium, and 15 to 20 per cent tungsten. The alloy is melted in the electric furnace and cast into moulds; it is not suitable for rolling or forging.

The degree of red-hardness is very high as will be seen from Fig. 140. At about 600 °C. the hardness (500 Brinell) is the same as that of the high-speed steel and above this temperature it is superior.

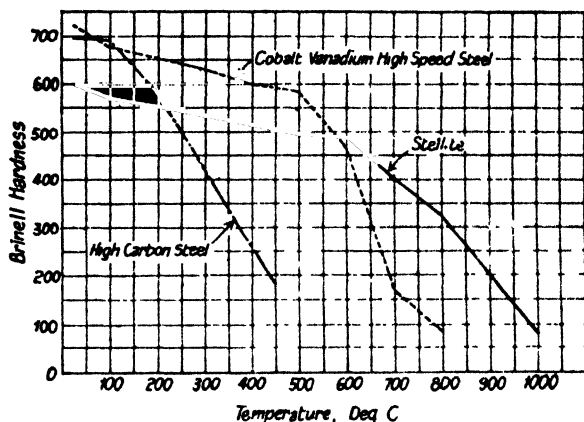


FIG. 140. ILLUSTRATING THE RED-HARDNESS OF STELLITE

moreover, at 1000 °C. it has the same hardness as the high speed steel at 800 °C.

Stellite is non-magnetic, non-corrodible, resistant to the majority of acids and possesses a low coefficient of friction. It is used either in the form of bits or tips brazed to shanks of 0.40 to 0.55 per cent carbon steel or as tool bits mounted in suitable holders. The front and side clearances are about 6° and the top rakes are kept fairly low.

Stellite is also used as a hard facing material for engineers' gauges, aircraft and automobile valve seatings and facings and also for the impact tips on valve stems. the Grade 60 is employed for this purpose on account of its high erosion and heat resistance. The wearing surfaces of valve rocker arms and pads are often coated with Stellite.

The method of applying Stellite for hard facing is with the oxy-acetylene blowpipe or electric arc, the material being melted and run into position.

Some other applications of Stellite include the facing of lathe centres, bending dies, burnishing broaches for steel tubes, cams, chuck jaws, header dies, hot drawing, blanking, shearing, trimming,

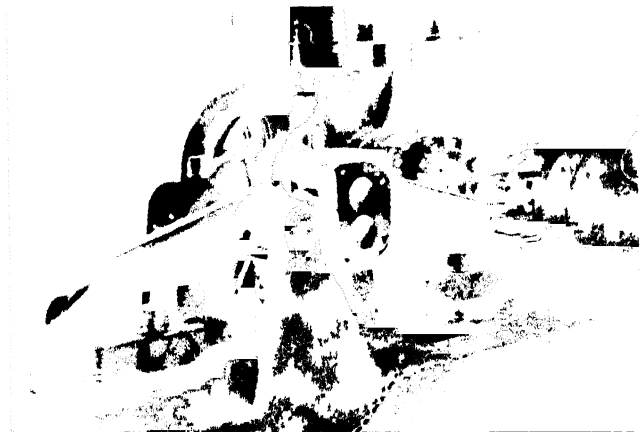


FIG. 141 MILLING CUTTERS WITH STELLITE INSERTED BLADES, MACHINING CAST IRON EXHAUST MANIFOLD AT 120 FT. PER MIN. $\frac{1}{16}$ IN. CUT AND .01 IN. PER MIN. FEED.



FIG. 142 ROUGH TURNING STEEL SHAFT WITH STELLITE TOOLS AT 95 FT. PER MIN. WITH $\frac{1}{16}$ IN. CUT AND FEED OF 0.017 IN. PER REV.

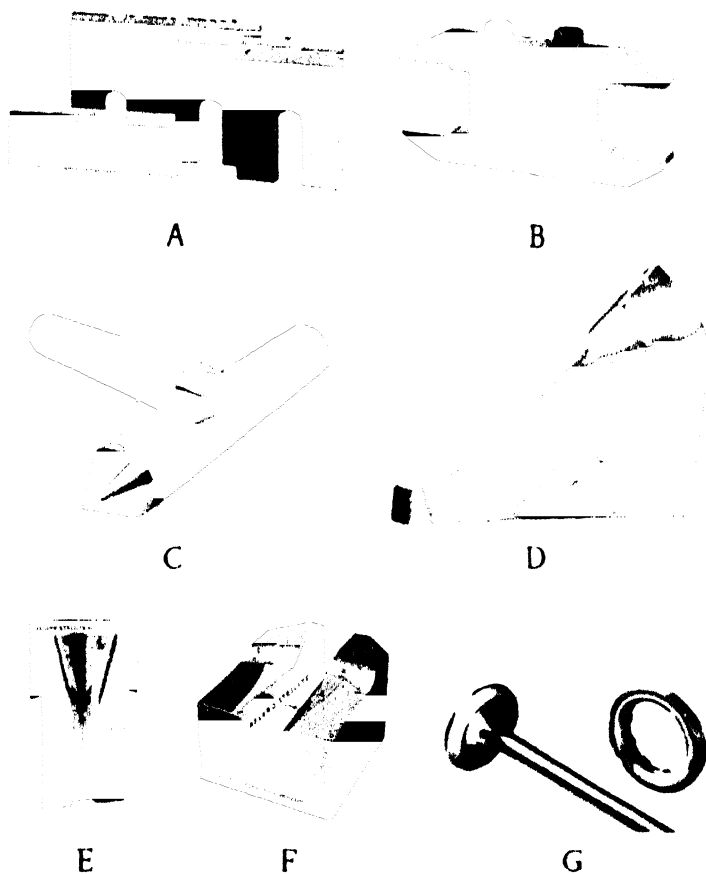


FIG. 143. SOME TYPICAL APPLICATIONS OF STELLITE PARTS

A — Stellite tipped wood cutting irons.

B — This inexpensive go and no go gauge has been heat treated with Stellite, and therefore will remain on size much longer (periods before requiring regrinding and re-setting).

C — Stellite lathe centres such as these permit faster turning without fear of burning the centre and will retain their accuracy much longer than centres of hardened steel.

D — This steel ploughshare showed remarkable results after being Stellite'd. It ploughed ten times the acreage of an unprotected ploughshare, and reduced the cost of replacements by more than one-half.

E and F — DeLoro-Stellite clamping and forming dies like these help to reduce steel sharpening costs by increased life and better efficiency. Stellite dies will sharpen from four to five times as many drills as ordinary dies and one mine reports a pair of clamping dies as having turned out 410,000 drills.

G — 14" engine valve and seating insert.

forming and upsetting dies, hot flash shaving tools, hot punches and shear blades, monotype moulds, snap gauges, ratchet gears, etc.

Three different grades of Stellite welding rod, namely, Nos. 1, 6 and 12, are available for hard facing purposes: the respective tensile strengths are 22, 38 and 31 tons per sq. in. and Rockwell hardnesses C 54, C 43 and C 46. The material may be laid on steel surfaces in practically any thickness.

In regard to the *mechanical properties* of the tool material, the tensile strength of the Deloro-Stellite is 31.5 tons per sq. in.; compressive strength, 139.0 tons per sq. in.; Brinell hardness at room temperature, 600. Rockwell C 60 to 62; Cantilever strength ($\frac{1}{2}$ in. sq. bit with 1 in. overhang), 1.1 tons.

Boron Carbide

This extremely hard product of the electric furnace is a combination of the rare metal boron and carbon. It is so hard that it is claimed to be able to scratch other cemented carbides, being the next hardest material known to the diamond. It is unaffected by the strongest acids and alkalis. The compressive strength is 115 tons per sq. in. The coefficient of linear expansion is about two-thirds that of steel. It is little affected by temperatures up to 1000 °C. and is lighter than aluminium.

The boron carbide grains are used as abrasive products for grinding wheels (for grinding cemented carbide tools, etc.), abrasive papers, etc. It can be melted to the liquid phase and is therefore useful for self-bonded articles of extreme hardness, e.g. pressure blast nozzles. It is particularly suitable for the nozzles of sand blasting apparatus, and when moulded into pressure blast nozzles shows many thousand times the wear resistance of the best materials hitherto used for this purpose.

Boron carbide is also used for wire-drawing dies as a substitute for the diamond for drawing very fine wires in various materials. In other applications where intrinsic hardness and great wear resistance are required this material is finding new uses, e.g. as inserts, guides, tubes, etc. The material in question was developed in the laboratories of the Norton Co., Worcester, Mass., U.S.A.

Tungsten-Cobalt-Iron Alloys

A different type of cutting alloy developed under the name of Alloy 548 by the American G.E.C. contains no carbon. Normally it is comparatively soft and can be cast, forged or rolled. It acquires its cutting hardness by the process of dispersion hardening in a similar

manner to duralumin. A typical alloy* of this class consists of 50 per cent iron, 30 per cent cobalt and 20 per cent tungsten. It is heat-treated by rapid quenching from 1300 °C and temper hardening at 600 °C, to give a Rockwell hardness of C 68 (about 72S Brinell). The hot hardness of this alloy has been shown to be higher than that of high-speed tool steel.

Die Steels

There is a fairly wide range of steels used for the dies of presses, moulding machines, blanking, trimming and threading dies and punches, the actual grade of steel employed depending upon the particular duty to be performed.

For some purposes plain carbon steels suitably heat treated, are employed; these have carbon contents of 0.6 per cent to 1.4 per cent, according to the nature of the work required. The following table may serve as a rough guide in this connection.

TABLE 78
CARBON STEELS FOR DIES AND PUNCHES

% Carbon	0.6	0.8	0.9	1.0	1.2	1.4
Application	Hot working and drop forging dies	Forging dies Hammer dies Large sheet knives	Punches Drop dies for cold work Cutting and blanking dies	Forming dies Small punches Cutting and trimming dies	Threading dies Cold stamping dies Textile cutting dies	Draw dies Trimming dies Cutting dies

In general the hardness and resistance to wear or abrasion, of a die steel increase with the carbon content, but the toughness is lowered, so that the steel must be selected with the most suitable carbon content to give the required degree of hardness and toughness.

The alloy die steels are employed in instances where the working conditions are sufficiently severe to limit appreciably the useful life of dies, punches, etc., made in carbon steels. From what has been mentioned in the earlier part of this chapter, the effects of the various alloying elements are to impart, in each case, desirable characteristics, such as improved toughness, hardness, tensile strength, shock-resistance, to the steel.

In the case of large dies the addition of chromium, up to about 3½ per cent, to steel not only increases the wear resistance and hardness,

* "Survey of More Recently Developed Cutting Materials," H. W. Pinder, *Wild Barfield Heat Treatment Journal*, September, 1939.

but also enables larger sizes of dies to be hardened uniformly throughout. With still higher chromium content a highly satisfactory steel is obtained for drawing, forging and cold trimming dies, suitable for working upon high-tensile alloy steels.

The wear resistance of die steel is also increased by *the addition of tungsten*, usually about 1 per cent of this element is employed for this purpose in plain carbon steels employed for punches and dies subject to severe working conditions, e.g. for the production of large quantities of components.

A higher percentage of tungsten, namely, from $3\frac{1}{2}$ to 10 per cent, gives still greater wear resistance and has the additional advantage of enabling the parts made therefrom to operate at elevated temperatures without losing hardness.

A special grade of high-chromium steel containing small percentages of other elements, known as Firth's Dichard, is recommended for blanking, drawing and forming punches and dies, cold trimming dies, built up blanking dies, and dies for drop forging hard materials such as *stainless steels*. Punches and dies of this steel are specially resistant to abrasion.

Low tungsten-chromium steels are used for heavy punching work and for pressing operations on stainless steels of the "Staybrite" class.

Medium tungsten-chromium steels are employed for cartridge drawing dies and in general for the working of brass and copper.

High tungsten-chromium steels are especially applicable for hot and cold forming dies for copper, brass, bronzes and similar alloys; for dies used in making intricate stampings; hot rivet, nut and bolt dies; hot and cold heavy duty punches and shears; extruding dies for brass and other alloys; *dies for die-casting aluminium, brass and zinc alloys*, and, incidentally, for springs working at elevated temperatures.

More recent high-grade die steels contain chromium, nickel and vanadium, the latter element being added to provide a wide range of heat-treatment and to inhibit excessive grain growth. The molybdenum is employed to give a high hardness number and improved hardness after tempering. A typical heat-treatment is pack hardening and air quenching from 980° C., followed by tempering at 205° C. for 3 hours. This gives a hardness of about 850 Brinell, with practically negligible distortion.

Non-shrinking Steels

These steels are characterized by their very low shrinkage after heat-treatment and comparative absence of warping or distortion, provided the correct heat-treatment process is employed. Such steels

usually have about 1.0 per cent of carbon and low tungsten and chromium content.

A typical percentage composition is as follows: C, 1.0; Mn, 1.00 to 1.25; W, 0.5; Cr, 0.5. This steel is annealed after forging and prior to machining by heating slowly to 800° C., and soaking at this temperature for a sufficient period of time to allow complete heat penetration. It is then allowed to cool in the furnace or in infusional earth, mica, lime, or any similar medium that will permit of uniform slow cooling.

The steel is *heat-treated* by heating it very slowly to a dark-red heat (about 650° C.), and then raising the temperature more rapidly to 788° C. to 815° C., holding it at this temperature for complete penetration of heat.

It is then quenched from this temperature in light oil, but it is not cooled below the temperature of boiling water (100° C.).

Tempering is carried out by reheating immediately in oil or other heating medium at a temperature of 163° C. to 204° C., holding for one half-hour and quenching in hot water. Intricate or small sections are quenched in oil or air.

Other commercial non-shrinking steels are preheated to 780–800° C. and after soaking at this temperature are heated quickly to 1000°/1050° C. and cooled in an air blast. Tempering at 200–250° C. then follows.

Non-shrinking steels are employed for dies and punches of delicate design; dies for moulding plastic materials; small and complicated gauges and jigs, taps, blanking and threading dies; and for special shear blades, cold press dies, and punches.

Special Chisel Steels

Following an extensive research* into the properties of steels suitable for cold chisels for locomotive works' use, a nickel steel was developed, having excellent properties. The percentage composition of this steel was as follows: C, 0.38 to 0.42; Mn, 0.6 (max.); Ni, 3.0 to 3.5. The most satisfactory results were obtained by heating the whole of the tool to 900°/950° C. and quenching the cutting portion for about 4 in. in raw linseed oil. Before heating for quenching the cutting edge should be ground after forging and not after heat-treatment. When heat-treated the cutting edge had a maximum diamond hardness of 700, the hardness diminishing, progressively, from the edge to a value of about 400 at 1½ in. from the edge. In subsequent use the steel becomes "work-hardened." Another suitable chisel steel, developed by Messrs. Samuel Osborn, Ltd., with a view to

* Presidential Address, Inst. Mech. Engrs., Sir H. Fowler, 1927.

resisting "mushrooming" of the head, but without any tendency to brittleness is a $3\frac{1}{2}$ per cent nickel-chromium steel. The heat-treatment recommended is as follows:—

"After forging, heat the head of the tool to 650°C . (a dull red heat) and allow to cool. This will produce a softened head, but one which will be sufficiently tough to prevent excessive spreading. The hardening is effected by heating the cutting edge to a temperature of 900 – 950°C . (light red heat) and allowing the tool to cool naturally in air."

After this treatment the cutting edge can be filed. A chisel of this steel has been driven cold through a $2\frac{1}{2}$ in. block of 30-tons tensile strength steel without damaging the edge or spreading the head.

V. Spring Steels

The most suitable materials for springs are those that can store up the greatest amount of work, or energy, in a given weight or volume of spring material, without permanent deformation.

Steel for springs should have as high an elastic limit as possible, and a corresponding high deformation or deflection value; further, it is essential for aircraft and automobile purposes that the spring steel should possess maximum strength against fatigue effects and shocks.

The steels most commonly employed for spring-making purposes include the high carbon steels, chrome-vanadium, silicon-chrome, silico-manganese and manganese-chrome steels.

Carbon Steels. Carbon spring steels possess the advantage that they are comparatively cheap to make and easy to manipulate, moreover, they give satisfactory results for very many commercial purposes.

The carbon content depends upon the purpose of the steel and usually lies between 0.6 and 1.1 per cent, with 0.2 to 0.5 per cent silicon and 0.6 to 1.0 per cent manganese. Carbon spring steels are made from the highest grades of iron, such as Swedish irons, with suitable additions of carbon and other constituents.

These steels are oil or water quenched from 780°C . to 840°C .—according to the composition—and afterwards tempered at 200°C . to 500°C . to suit the particular application.

A typical carbon spring steel is that conforming to D.T.D. 5A (wire) and has the following percentage composition: C, 0.7 to 0.8; Si, 0.3 (max.); Mn, 1.0 (max.). When oil-hardened at 780°C . it has a tensile strength of 95 to 120 tons per sq. in.

The carbon spring steels are used for laminated springs for locomotives, carriages, wagons, and sometimes for heavy road vehicle

springing purposes. The higher carbon content oil hardening steels are used for volute spiral and conical springs and for certain types of petrol engine inlet valve springs.

Chrome-vanadium Steel. This belongs to the high quality spring steel class and contains from 0.45 to 0.55 per cent carbon, 0.90 to 1.2 per cent chromium, 0.15 to 0.20 per cent vanadium, 0.30 to 0.50 per cent silicon, 0.50 to 0.80 per cent manganese. The steel mentioned gives uniformity in hardening and freedom from internal stresses. It has a high elastic limit and resistance to fatigue and impact stresses, moreover, it machines without difficulty and can be given a smooth surface free from tool marks.

The following results were obtained from a 1.0 per cent chromium and 0.15 per cent vanadium spring steel* which was hardened and tempered to give the three different Brinell hardness values stated; a further specimen was deliberately quenched from 150 °C above the correct temperature and tempered to give about 400 Brinell.

TABLE 79
CHROME-VANADIUM STEEL TEST RESULTS

Mark	Elastic Limit (Tensile) (lb./sq. in.)	Yield Point (Tensile) (lb./sq. in.)	Max. Stress (Tensile) (lb./sq. in.)	Elongation (in. in 8 in.)	Reduction of Area (per cent)	Elastic Modulus (lb./sq. in.)	Brinell Hardness	Impact (ft.-lb.)
A	12.50	87.00	96.0	5	38.0	13001	4.6	11.0
B	18.24	78.12	84.02	7.0	33.5	13323	40 [†]	23.7
C	42.86	68.0	71.15	10.0	45.7	13445	5	42.7
D*	19.0	73.47	84.10	6.5	30.6	13180	5.01	11.3

* D represents the deliberately mal-treated specimen.

If these results are compared with those given for silicon-manganese steel on page 301, it will be seen that for similar Brinell hardness or tensile strength values, this steel has a higher elastic limit, a slightly higher elastic modulus and a distinctly higher resistance to failure by impact.

The strength properties of chrome-vanadium spring steel of the following composition, namely C 0.45 to 0.55, Mn 0.85 to 1.00, Cr, 1.00 to 1.25 and V 0.15 to 0.20, are shown in Fig. 144.

This steel was oil-quenched from 850 °C.

In general the tensile strength of the oil-quenched chrome-vanadium spring steels at 850 to 870 °C varies from 90 to 110 tons per sq. in.

* "Road Vehicle Springs," S. Fox & Co. Ltd., Sheffield.

† "Vanadium in Steel," High Speed Steel Alloys Ltd., Widnes.

This steel is forged between 1050–1100° C. down to 900° C. (min.). It is hardened, as stated, by oil quenching at 850° to 870° C. and tempered for vehicle and other spring purposes at 470° to 510° C.

Chrome-vanadium spring steel is used for motor car laminated and coil springs for suspension purposes, automobile and aircraft

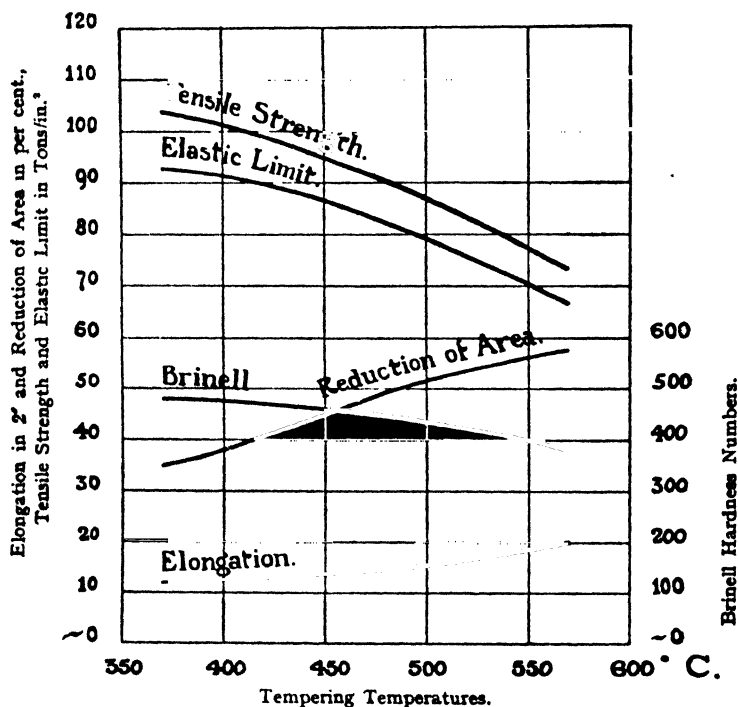


FIG. 144. MECHANICAL PROPERTIES OF CHROME-VANADIUM SPRING STEEL.

engine valve springs, and in general for high-grade engineering coil and laminated springs, etc.

Silico-chrome Steel. This spring steel, although not so good as the chrome-vanadium and silico-manganese steels, has been used in the past in preference to high-carbon steels.

The percentage compositions lie between the following limits, namely, C, 0.55 to 0.65; Si, 0.5 to 0.9; Mn, 0.4 to 0.8; Cr, 0.5 to 0.8.

When heat-treated by oil-quenching at 820° C. and tempering at 550° C. to 600° C., it has a yield point of 40–45 tons per sq. in.; tensile strength of 60–75 tons per sq. in.; elongation of (2 in. \times 0.564 in.

diam.), 15-18 per cent. reduction of area, 40-45 per cent. and Brinell hardness of 250-340.

This steel is suitable for leaf springs for motor vehicles and rail-cars, also for suspension and compression helical springs for medium duty purposes.

Silico-manganese Steel. This is a high-grade spring steel containing from 1.8 to 2.0 per cent of silicon and 0.8 to 1.0 per cent of manganese with about 0.5 to 0.6 per cent carbon. It is the usual standard quality modern spring material, and is much used for many engineering purposes. The results of tests made upon samples of this steel heat-treated so as to give the Brinell hardness values stated are as follows--

TABLE 80
SILICO-MANGANESE STEELS TEST RESULTS

Mark	Elastic Limit (Tons per sq. in.)	Yield Point (Tons per sq. in.)	Max. Stress (Tons per sq. in.)	Elongation per cent on 5 in.	Reduction of Area per cent	Elastic Modulus (Tons per sq. in.)	Brinell Hardness (N)	Impact (Ft.-lb.)
A	45.60	87.40	99.22	6.0	40.1	13183	456	7.8
B	48.70	71.80	81.66	8.2	29.9	13129	398	5.3
C	44.96	58.07	68.41	14.0	40.3	12650	332	16.8
D	37.00	63.84	79.07	10.5	28.2	13164	378	6.0

This steel is forged at 1050-1100° C. down to 900° C. (min.). It is heat-treated by oil quenching at 900° C. and tempered at 500-550° C.

Manganese-chrome Steel. This more recently introduced spring steel is used as an alternative to silico-manganese steel, and has certain merits of its own. It has about the same general mechanical properties as the latter steel and is heat-treated by oil-quenching at 820° C. and tempering at the somewhat lower temperatures of 410-450° C.

Aircraft Engine Valve Springs

These are usually made of the D.T.D. 5A carbon steel, previously mentioned, or of chrome-vanadium steel containing 0.40 to 0.50 C, 1.0 to 1.5 Cr, and 0.15 V (percentages). The springs are wound soft and afterwards heat-treated to give a tensile strength of 90 to 120 tons per sq. in. It is important to reject any springs showing surface defects, as these invariably lead to failure; the magnetic method of testing is now employed for detecting such defects. The wire employed for high-grade valve springs is ground and cadmium plated. In order to avoid any possibility of spring failure aircraft engines have more recently been using an oil-hardened and tempered carbon steel (0.65 to 0.70 C), which is coiled first and heat-treated afterwards, to give a

tensile strength of 90 tons per sq. in. (min.) with 8 per cent elongation. This material is similar to that used with highly satisfactory results on automobile engines, where failures are extremely rare. The springs are shot-blasted for 30 min., with $\frac{1}{2}$ in. diameter shot and 20 lb. per sq. in. air pressure; this operation results in surface hardening which results in an increase in fatigue strength up to 25 per cent.*

The carbon steel wire, when made from Swedish iron by the acid open-hearth process, is singularly free from inclusions, but it is essential to remove any surface marks or defects which otherwise would cause fatigue cracks, by shot-blasting which is equivalent to ball-peening in its smoothing and hardening effects. The results of this shot-blasting have been shown to increase the fatigue stress range. Thus, in the case of a high grade carbon spring steel widely used for motor car engine valve springs the fatigue range before shot-blasting on a testing machine was 9 to 31 tons per sq. in., and after shot-blasting, 9 to 51 tons per sq. in. The springs are usually tested for surface defects by the Magnaflex magnetic detection method, before passing for service. Stainless steel has been employed, experimentally, for valve springs on account of its corrosion resistance qualities, but its lower fatigue resistance has hitherto been its principal drawback to more general use.

VI. Valve Steels

The valves of internal combustion engines work under somewhat exacting conditions in regard to high operating temperatures, repeated impacts at high frequencies, wear effects and exposure to corrosive hot gases.

The inlet valve around which flows the relatively cool fuel-air mixture during the induction stroke has appreciably lower working temperature than the exhaust valve, which in modern engines may actually run at a red heat in some instances, usually its temperature lies between 750 °C and 850 °C, under full power conditions. The exhaust gases contain carbon dioxide and steam; these have a corrosive action upon the valve material. With leaded fuels, the lead salts also have a chemical action on the valve steel. The desirable qualities for a suitable exhaust valve material are, briefly, as follows: (1) Maximum tensile strength at working temperatures; (2) maximum impact or notched bar value; (3) minimum scaling or corrosive tendency; (4) ease of forging, and (5) freedom from inclusions or cracks.

The inlet valve should also possess similar qualities, but the resistance to corrosion is unimportant since only the valve head is here

* "Materials of Aircraft Construction," H. J. Gough, *Aeron. Soc. Journ.*, 1938.

concerned. Usually a nickel-chrome high tensile steel is quite suitable for the inlet valve and this type of steel is much used in automobile practice. On the other hand in a few cases the inlet valve is made of the same material as the exhaust valve in order to facilitate interchangeability and to simplify the matter of spare parts.

In the past various materials used for valves have included plain carbon steels, low-nickel and nickel-chromium steels, ordinary steels with cast-iron heads, tungsten, stainless, silicon-chrome, cobalt-chrome and high nickel-chromium steels. As a result of much investigation and experience with these materials modern high-speed petrol engines employ certain alloy steels for their exhaust valves, possessing the desired qualities.

It may be of interest to give a brief summary of the results of a fairly extensive and complete series of tests* upon valve steels suitable for high-speed engines. The results of this investigation afford a useful guide to the selection of the more suitable valve steels.

The steels used together with their analyses and heat treatments are given in Table SI.

TABLE SI
COMPOSITIONS AND HEAT TREATMENTS OF VALVE STEELS

Steel	Analysis										Treatment	
	C	Si	Mn	Cr	Ni	V	W	Co	Mo		Hardening	Tempering
3 nickel-chrome	0.43	0.25	0.45	0.7	2.8				1		760 C oil	625 C oil
Stainless steel	0.40	0.85	0.44	13.00							1000 C oil	700 C air
Silicon-chrome	0.34	2.0	0.13	8.20			1.0				1000 C air	800 C air
Chrome steel	0.61	0.34	0.40	0.8							1000 C air	700 C air
Cobalt-chrome	1.50	0.42	0.27	13.2					0.72		1000 C air	750 C air
High speed steel	0.73	0.16	0.18	3.78		0.1	1.85				950 C air	800 C air
High nickel-chrome	0.45	1.75	0.6	1.67	12.81		2.1				Normalized	800 C
	0.40	1.83	1.16	13.20	2.23		3.11					
	0.45	1.47	0.9	11.30	1.10							

The high nickel-chromium steels belong to the austenitic class and, in general, are rather softer than most of the other steels, and therefore have not such good wearing qualities. Moreover they have higher expansion coefficients—a factor which is a disadvantage in certain types of engines. On the other hand they are better able to retain their strength at high temperatures and resist hot corrosion satisfactorily.

* "Valve Steels," P. B. Honshaw *Journ. Roy. Aeron. Soc.*, 1926

The mechanical properties of the valve steels given in Table 81 at atmospheric temperatures, are given in Table 82.

TABLE 82
MECHANICAL PROPERTIES OF VALVE STEELS (COLD)

Steel	Tensile Test					
	Elastic Limit Tons	Max Stress Tons	Elong on 2 in per cent	Red of Area per cent	Brinell	Izod Impact Ft lb
3% nickel chrome	48.5	56.5	23	62.5	255	66
Stainless steel	47	48.3	24	58.1	228	50
Silicon chrome	51	63	21	40	302	9
Chrome steel	42	54	24.5	55	228	28
Cobalt chrome	42	58	13	22	255	4
High speed steel	46	61	15	24	269	5
High nickel chrome	42	68	27	45	269	55

The steels in question cannot, of course, be judged from their cold test properties alone, since they have to operate under high temperature conditions, namely, between about 700° C. and 850° C. in most instances. It is therefore necessary to compare their strength properties under working temperature conditions, as shown in Table 83.

TABLE 83
MECHANICAL PROPERTIES OF VALVE STEELS (HOT)

Steel	Tensile Strength—Tons per sq. in.				
	600° C.	700° C.	800° C.	850° C.	900° C.
3% nickel chrome	34.0	13.5	9.2	6.9	4.5
Stainless steel	24.2	10.2	6.1	5.6	7.9
Silicon chrome	42.0	25.3	10.7	7.2	3.9
Chrome steel	36.5	19.0	7.0	7.2	7.3
Cobalt chrome	45.0	24.8	10.0	5.8	8.1
High speed steel	41.0	21.3	9.8	7.7	8.5
High nickel-chrome	42.6	33.8	24.0	19.4	15.0

Since the properties of possible steels for valve purposes are of the greatest importance at high temperatures, a summary of the test results for the steels given in Table 81 is included, these results are shown in Table 84 and indicate the strengths, hardnesses and ductilities at the high temperatures of 850° C. and 900° C.—temperatures above

TABLE 84
MECHANICAL AND SCALING TEST PROPERTIES OF VALVE STEELS

	Tem- perature (C)	Tensile Strength Tons per sq. in.	Elonga- tion per cent on 2 in.	Brinell Hardness (before test)	Izod Impact ft.-lb.	Izod Impact at 15° C. ft.-lb.	Scaling Tests at 1000° C. Wt. Loss per sq. in. per hour, in grammes
3% nickel-chrome	850	69					
	900	43	30	286			
Stainless steel	850	36	46	286			
	900	29	21	286			0.2197
Silicon-chrome	850	72		291			
	900	39	36		77-78	4	0.0254
Chrome steel	850	72					
	900	74	20	286	74	37	0.2985
Cobalt-chrome	850	88	13	269			
	900	81	17	269	20-22	5	0.1418
High-speed steel	850	77	13	277			
	900	85	23	277		6	0.3993
High nickel-chrome steel	850	19.4	30	269			
	900	15.0	28	269	"	2	0.0563

those likely to occur in the case of ordinary petrol and Diesel engines. The results indicate the superiority of the high nickel-chrome steel in tensile strength combined with good ductility and hardness, and a satisfactory impact value. It also possesses excellent anti-scaling properties, being second only to silicon-chrome steel in this respect. The high nickel-chrome steel exhibits the characteristic stiffening effect of the air-hardening steels at about 900° C.; this is apparent by the reduced elongation at this temperature. All air-hardening steels, it may be noted -- with the exception of silicon-chrome steel -- reach their lowest hardness at 900° C.; at 850° C. they all show signs of "stiffening" again. Silicon-chrome steel, on the other hand, begins to harden a little at 950° C. and reaches its maximum hardness at 1000° C.; it is fully hard when cooled from the latter temperature. Another important property of silicon-chrome steel is its high notched bar (Izod impact test) value at high temperatures. Although, as shown by the results in Table 84, the value is only 4 ft.-lb. at 15° C., it increases with temperature to 77/78 ft.-lb. at 900° C., being over twice the value for high nickel-chrome steel. The only drawback to the use of this steel for valves is the possibility of breaking a valve when starting the engine from the cold; in this respect the high nickel-chrome steel has a marked advantage in its high "cold" impact strength.

In regard to the expansion coefficients for the valve steels considered, these are practically the same for all the steels, between 0° C. and 800° C., with the exception of the high nickel-chrome steel, the value for

which is about 20 per cent greater at 800° C. than for the other steels, at 400° C. the expansion coefficient is about 40 per cent greater.

A general conclusion that can be made from the results given is that the high nickel-chrome steel has the best all-round qualities for an exhaust valve steel of the steels tested; these results have also been confirmed by practical tests with exhaust valves made of this material, another point in its favour is that it is about the easiest of the steels considered to make into valve forgings.

Some Typical Modern Valve Steels

Apart from the high nickel-chrome or heat-resisting steels considered, other steels that have given very good results in automobile engines are the silicon-chrome ones previously mentioned; these steels, in various compositions, are standardized to S.A.E. Specifications in America, and are known as Silchrome steels, typical modern steels of this group used for exhaust valves on American car engines are Sil-X, Sil-I, Sil XB and Sil XCR. The following are the percentage compositions of the three latter valve steels.

TABLE 85
COMPOSITIONS OF SILICON-CHROME STEELS

Steel	C	Mn	Si	Ni	Cr	Mo
Silchrome No. 1	0.4-0.5	0.4-0.6	3.50-4.25	0.50	7.5-8.5	-
Silchrome XCR	0.4-0.5	1.0 (max)	1.0 (max)	4.5-5.0	23.0-24.2	2.5-3.0
Silchrome XB	0.6-0.86	0.2-0.6	1.25-2.75	1.0-2.0	19.0-23.0	-

The two latter steels are superior to Silchrome No. 1 as valve materials, the Silchrome XCR being the best exhaust valve steel and coming next to the Stellite-faced valves in its hardness and wear-resisting properties; it has a coefficient of expansion between the ferritic and austenitic steels but a rather low impact value.

The austenitic valve steels, e.g. high nickel-chrome, are used for high-duty engines, in conjunction with Stellite valve seatings, but proper allowance must be made for their higher expansion coefficient; in this respect it is necessary to give the valve stems a high surface finish in order to avoid valve guide "pick-up" or sticking effect. The thermal conductivity of these steels is lower than for silicon-chrome ones, so that the valves tend to run better than the latter in practice.

A typical austenitic valve steel, conforming to the Air Ministry

D.T.D. 49B Specification has the following percentage composition: C, 0.35 to 0.45; Cr, 12.4 to 14.5; Ni, 12.5 to 14.5; Mn, 0.5 to 1.0; Si, 1.00 to 1.75; W, 2.00 to 3.00.

In the case of austenitic valves it is necessary to provide the valve stem with a hardened tip for the tappet contact area. It is now usual to weld a button of hardened steel or to Stellite the tip of the stem;

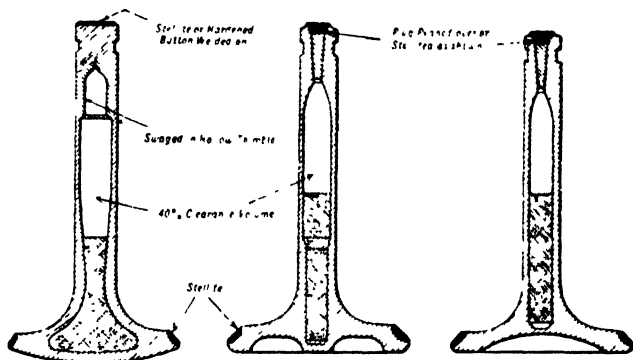


FIG. 145. TYPES OF SODIUM FILLED AIRCRAFT ENGINE VALVES

as the Stellite has a rather poor impact value, the hardened steel tip is generally preferable.

Mention should also be made of the sodium-filled valves used for high-duty aircraft engines. An austenitic steel valve, with hollow stem containing sodium, a hardened steel valve stem button and a Stellite face, is often employed for this purpose (Fig. 145).

A typical austenitic steel used for aircraft engine exhaust valves is one containing Ni, 13.0 per cent, Cr, 13.0 per cent, and W, 2.5 per cent. The stem is sodium-filled and its exterior is nitrided. The head and seating face in some cases are covered with an 80/20 per cent nickel-chrome alloy; the seating employed with this type of valve is Stellite.

Experiments have also been made with exhaust valves made entirely of 80/20 nickel-chrome alloy.

The use of a high expansion coefficient nickel-chromium-manganese steel for valve insert rings of aluminium cylinder heads is another more recent development in aircraft engine design.

Steels Containing Beryllium

Small percentages of beryllium in association with chromium and nickel have been found* to improve the corrosion resistance of iron

* "Beryllium and Its Alloys," H. A. Sloman. *Metal Industry*, 23rd February, 1934.

alloys so that they are practically as good as the stainless steels, while at the same time possessing excellent strength, hardness and elasticity. A typical example is that of an iron alloy having 12 per cent chromium, 5 per cent nickel and 1 per cent beryllium, which attains the temperature of high-speed steel after ageing.

Another alloy having 30 per cent nickel and 1 per cent beryllium resembles the Invar steels, and in addition to excellent corrosion resistance, has a high tensile strength when suitably tempered.

It is of interest to note that certain beryllium-iron alloys containing no carbon possess appreciable residual magnetism.

CHAPTER VII

NITROGEN HARDENING STEELS AND IRONS

Nitrogen as a Hardening Agent

It was known as long ago as 1905 that iron when heated to redness in contact with ammonia would readily absorb nitrogen. It was established some twenty years later by Fry of Essen that there were several possible iron-nitrogen combinations, e.g. Fe_2N and Fe_4N , as well as a solid solution of low nitrogen content. It was also demonstrated that steels which have absorbed nitrogen experienced a peritectoidic change at a definite temperature, namely, 580 °C. for iron and from 600 °C. upwards for alloy steels, such that if nitrogen is absorbed below this change-temperature it enters into a solid solution as distinct from a nitride.

The process of exposing steels to nitrogen containing gases such as ammonia at the appropriate temperatures, for definite periods of time, followed by quenching, is known as the *Nitriding Process*, and the alloy steels employed for this process are defined as *Nitralloys*. Among the steels that were investigated by Fry were those containing aluminium, chromium, molybdenum, tungsten, titanium and vanadium, and it was shown that such steels formed nitrides of high nitrogen content. Of these elements, aluminium was found to give the best response to nitriding, both in the amount of nitrogen absorbed and in the stability of the aluminium nitride formed, even when heated to 1000 °C. It is not, however, essential for a steel to contain aluminium, there being several alternative alloy steels used for nitriding purposes which contain other elements than aluminium. The more recent Nitralloy steels have improved mechanical properties for the core and better machinability.

Briefly, the process of nitriding consists in exposing the machined parts to the action of ammonia gas in an electric furnace at a temperature of about 500 °C. for a period of 40 to 100 hours, depending upon the depth of case required, the latter increases with the period of exposure up to a depth of about 0.03 in. (0.8 mm.) for 100 hours exposure.

Advantages of Nitriding

The principal advantage of this process, when applied to suitable alloy steels, is that the case obtained *is much harder than that which is possible with the best case-hardening steels*. The hardness is such that

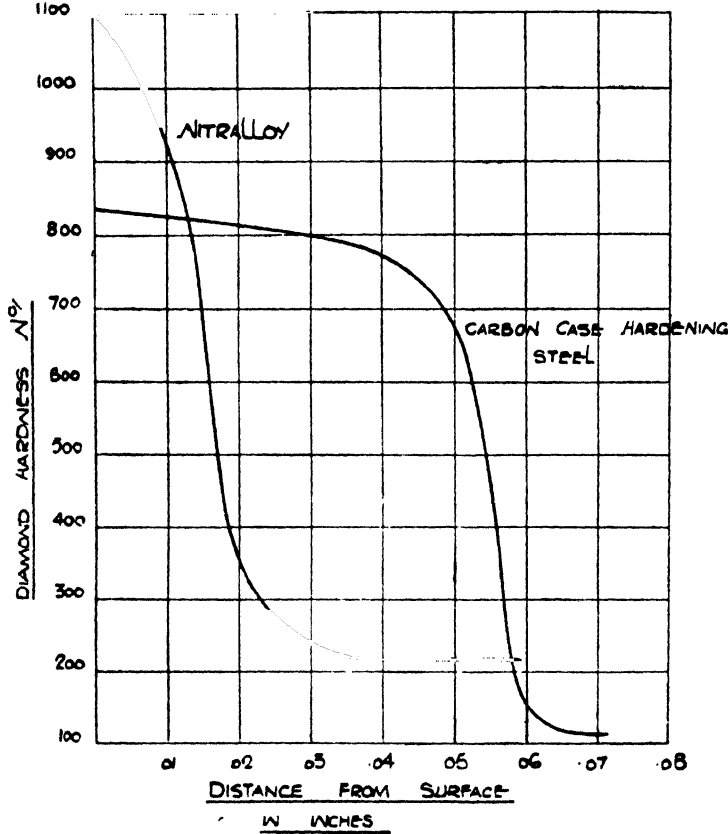


FIG. 146. A COMPARISON OF THE CASE HARDNESSES OF NITRALLOY AND CASE-HARDENING STEEL

the case will cut glass. The hardness values converted from readings of a Herbert pendulum hardness tester range from 900 to 1100 Brinell, and with the Shore scleroscope readings, 102 to 113.

The following comparative hardness values* are given for a nitrogen-hardening steel and some of the hardest other steels and cast irons—

TABLE 86
HARDNESS VALUES OF STEELS AND CAST IRONS

Material	Diamond Hardness Number
Nitralloy	1050-1150
Chrome-vanadium steel (0.5% C; 1.0% Cr, 0.2% V) Case hardened	800-900
High-speed tool steel, Hardened	800-900
1.5% carbon tool steel, Hardened	850-900
Tool steel (12% Cr; 1% V; 2% C), Hardened	750-850
Carbon steel, Case-hardened	750-850
Hard white cast iron	500
Grey cast iron	210

On account of its superior hardness the nitrided case has *superior wearing qualities* to other hard surfaced steels. Thus, it has been shown, in connection with wear tests made on an Amsler machine under a load of 80 kilos, that the wears in centigrammes of case-hardened chrome, nickel-molybdenum, chrome-vanadium and chrome-nickel-molybdenum steels were 2.98, 2.47, 2.08, and 2.79 respectively, whilst for Nitralloy steel no measurable wear could be detected under similar test conditions.

Another advantage of the nitriding process is that it is carried out at the low temperature of about 500° C. as compared with 850° C. to 900° C. for case-hardening methods. As a result there is *far less risk of distortion* provided that all stresses set up in the steel by working or machining have previously been removed by stabilizing above 500° C.

The nitriding process leaves the steel parts *with a clean finish*, there being no scale, dirt or other deposits. The surfaces are perfectly clean with a grey matt surface; sometimes this is tinted with blue and pink colours.

A *slight growth* of about 0.001 in. on diameter occurs as a result of the nitriding process; as this is quite regular and uniform it can be allowed for in the design or machining dimensions

* Nitralloy Ltd., Sheffield.

The nitrided case retains its hardness when the part is reheated to the temperature at which the treatment is applied, namely, about 500° C., whereas case-hardened steels commence to lose hardness at temperatures as low as 180° C. to 120° C.

Polished nitrided steel does not heat up when running with aluminium alloys. For gudgeon pins and cylinder walls finished by nitriding, this is a definite advantage.

The nitrided case shows considerable resistance to corrosion by moist atmospheres, fresh and sea water and steam, provided the grey film is left on the metal after nitriding.

Another important feature of nitrided steels is that they are practically immune from the weakening effect of notches; this is a marked advantage from the point of view of fatigue resistance under alternating and repeated stresses. Extensive tests have shown that practically the same results relative to fatigue strength are obtained when a part is notched and then nitrided as when the part is unnotched and nitrided. With hardened alloy steel bars the effect of notching is to reduce the fatigue resistance.

It has also been shown that the *corrosion fatigue resistance* of nitrided steels is of a relatively high order. Tests carried out in Tees River water showed the high ratio of *two-thirds* of the normal resistance value of the steel when tested in air.

Typical Nitralloy Steels

There is a number of Nitralloy steels available having different elements and proportions of these, and with varying carbon content. The variations in the latter are governed solely by the mechanical properties required from the steel forming the core, as the percentage of carbon, within normal limits, does not affect the hardness of the nitrided case. It is, however, important to limit the carbon content, as too high a percentage may affect the properties of the nitrided steel detrimentally.

The various grades of Nitralloy steels have carbon contents ranging from 0.20 to 0.50. The three standard grades (D.T.D. 87 Specification) are known as Grades 3, 5 and 7 respectively.

Grade 3 steel, after oil-hardening and tempering, cannot be softened much below 50 tons per sq. in. tensile strength, and is, therefore, reserved for parts which do not involve difficult machining and where maximum strength is required in the core. It is most frequently supplied with a tensile strength of 55 to 65 tons per sq. in., in the form of bars or forgings, oil hardened and tempered ready for machining outright.

Grade 5 steel allows of a softer steel after heat-treatment (45 to 55 tons per sq. in. tensile strength), and is recommended for parts involving more intricate machining. In most cases parts can be finish-machined outright from the oil-hardened and tempered material supplied.

Grade 7 steel, giving 35 to 45 tons per sq. in. tensile strength, is used

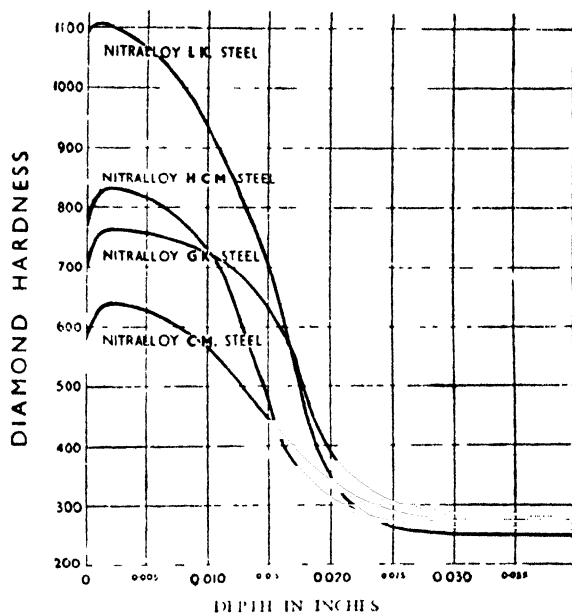


FIG. 147. TYPICAL HARDNESS DEPTH CURVES FOR NITRALLOY STEELS, SHOWING GRADUAL DIMINUTION OF HARDNESS FROM CASE TO CORE
(Firth Brown Ltd.)

for wearing parts where the surface pressures are not high, and is easily machinable in the hardened and tempered condition as supplied.

The test results given in Table 87 have been obtained on specimens made from $1\frac{1}{8}$ in. diameter hammered bars *

Other alloy steels to which the nitriding process can successfully be applied, apart from those containing aluminium, include *vanadium-chromium-molybdenum*, *chromium-nickel-molybdenum*, *high chromium-molybdenum* and *austenitic steels*, such as those of the *tungsten-nickel-chromium* class. The methods of nitriding austenitic steels for aero-engine valves, after removal of the passive film on the surface

* *Ibid.*, page 311.

TABLE 87
MECHANICAL PROPERTIES OF STANDARD NITRALLOY STEELS

Nitralloy Steel	Tempering Temperature	Yield Point Tons per sq. in.	Maximum Stress Tons per sq. in.	Elongation per cent	Reduction of Area per cent	120° Impact Ft.-lb.
<i>Grade 3</i>						
Oil hardening	600 °C	62.4	68.2	16.0	48.0	35
Temperature	650 °C	55.6	62.2	20.5	57.5	40
900 °C	700 °C	44.4	53.6	23.0	59.5	55
<i>Grade 5</i>						
Oil hardening	600 °C	48.8	62.4	19.0	53.0	44
Temperature	650 °C	44.0	57.6	23.0	60.5	54
900 °C	700 °C	38.0	50.6	28.0	65.0	67
<i>Grade 7</i>						
Oil hardening	600 °C	31.5	42.5	28.0	66.0	65
Temperature	650 °C	30.1	37.1	29.5	67.0	70
900 °C	700 °C	28.6	36.0	30.0	68.0	78
	750 °C	26.2	34.8	35.0	72.0	95

before nitriding, followed by plating, form the subject of patents held by Nitralloy Ltd., Sheffield.

Vanadium-chromium-molybdenum steels, to Air Ministry Specification D.T.D. 286A. These steels give a surface hardness, after nitriding, of 750-800 diamond number, and are chiefly employed for dies, moulds for plastics, and similar parts where a high degree of surface hardness is required with a first-class finish. They are also used for crankshafts.

Chromium-nickel-molybdenum steels, to Air Ministry Specification D.T.D. 228. These steels give a surface hardness of 600/650 diamond number after nitriding, but their increased toughness and resistance to fatigue make them eminently suitable for aero-engine and automobile crankshafts for which these steels are now being very widely used.

High chromium-molybdenum steels, to Air Ministry Specifications D.T.D. 306 (carbon 0.30 per cent) and D.T.D. 317 (carbon 0.20 per cent). These steels give 800-850 diamond hardness after nitriding, with 60/70 tons in the core for D.T.D. 306 and 45/55 tons for D.T.D. 317; they are being very widely used for aero-engine crankshafts and airscrew shafts. D.T.D. 317 steel is now in extensive use for aero-engine cylinders, for which purpose it has proved to be the ideal material.

A typical aluminium-content Nitralloy steel* contains from 0.20 to 0.50 per cent carbon; 0.25 per cent nickel; 1.4 to 1.8 per cent

* Messrs. T. Firth and J. Brown Ltd., Sheffield.

chromium; 0.9 to 1.3 per cent aluminium and 0.10 to 0.25 per cent molybdenum.

The effect of increasing the carbon content, whilst maintaining the other elements constant, is to improve the tensile strength and toughness, whilst not interfering in any way with the hardness of the nitrided surface layer. The full mechanical strength properties of the steel can be developed by suitable heat-treatment, such as quenching and tempering, before the parts are nitrided, as the latter treatment, being effected at about 500 °C., does not reduce the strength or hardness of the core.

The influence of the carbon content on the strength properties of Nitralloy steel is well illustrated in the case of the typical steel of the composition previously mentioned. In addition to the elements given, the steel contained 0.35 per cent silicon, 0.65 per cent manganese, 0.02 per cent sulphur and 0.02 per cent phosphorus.

The manner in which the mechanical properties of this steel are affected by the carbon content and also by heat-treatment is illustrated by the results given in Table 88, for the carbon range of 0.20 to 0.45 per cent and for three different degrees of hardness.

TABLE 88
PROPERTIES OF NITRALLOY STEELS

Percentage of Carbon	0.35 to 0.45			0.26 to 0.35			0.20 to 0.26		
	O.H.	900 °C.	T	O.H.	900 °C.	T	O.H.	900 °C.	T
	550 °C.	650 °C.	750 °C.	550 °C.	650 °C.	750 °C.	550 °C.	650 °C.	750 °C.
Yield point, tons per sq. in.	72.0	55.6	37.6	49.6	44.0	34.4	33.4	30.1	26.2
Max. stress, tons per sq. in.	80.0	62.2	47.0	66.4	57.6	43.2	46.8	37.1	34.8
Elongation, per cent	12.5	20.5	27.5	16.5	23.0	34.5	26.0	29.5	35.0
Reduction of area, per cent	43.0	57.5	58.5	50.0	60.5	68.5	62.0	67.0	72.0
Impact, Izod, ft.-lb.	23	40	65	32	54	75	61	70	95

Among the strongest of the Nitralloy steels are those containing about 0.5 per cent carbon and no nickel. A typical percentage composition is as follows: C, 0.50, Si, 0.35, Mn, 0.65, Cr, 1.60, Al, 1.10, and Mo, 0.20.

The following results were obtained from test pieces made from $1\frac{1}{8}$ in. hammered bars—

TABLE 89

PROPERTIES OF 0.5 PER CENT CARBON NITRALLOY STEEL

Oil hardening Temperature	Tempering Temperature	Yield Point Tons per sq. in.	Maximum Stress Tons per sq. in.	Elongation per cent	Reduction of Area per cent	Izod Impact Ft.-lb.
900 °C	550 °C	91.2	98.4	10.0	32.0	14
	600 °C	83.6	90.4	11.0	36.0	22
	650 °C	73.2	80.0	13.5	44.0	31
	700 °C	56.4	67.2	19.0	53.5	50

A typical Nitralloy steel without aluminium, which is suitable for aircraft and automobile crankshafts and gives after nitriding a surface hardness of 750 to 800 diamond, has the following percentage composition: C, 0.35, Si, 0.30, Mn, 0.50, Cr, 2.0, Mo, 0.25 and V, 0.15.

When oil-hardened at 900 °C and tempered at 600, 650 and 700 °C respectively, it gives the strength properties shown in Table 90.

TABLE 90

PROPERTIES OF FIRTH'S G.K. 3 NITRALLOY STEEL

Tempering Temperature °C.	Yield Point Tons per sq. in.	Maximum Stress Tons per sq. in.	Elongation per cent	Reduction of Area per cent	Izod Impact Ft.-lb.
600	61.2	70.0	17.0	57	50
650	56.0	62.0	20.0	61	57
700	46.4	52.0	24.5	66	76

Effect of Tantalum and Niobium

The rate of thickening of the nitrified layer can be increased considerably by the addition of tantalum or niobium in small percentages. Thus, 1 per cent niobium will produce a nitrified layer of 0.125 mm. thickness in 8 hours with a temperature of 550 °C; exposure for 24 hours gives a hardened layer of 0.3 mm.

The effect of niobium and tantalum is to reduce or eliminate the amount of active carbon, since these elements form carbides at the expense of the iron carbides. The nitrified steel can therefore be quenched at a high initial temperature without risk of cracking.

The period of the nitriding process is reduced and the nitriding temperature can be raised with niobium steels without introducing brittleness in the nitrided layer.

The beneficial effects of tantalum and niobium in increasing both

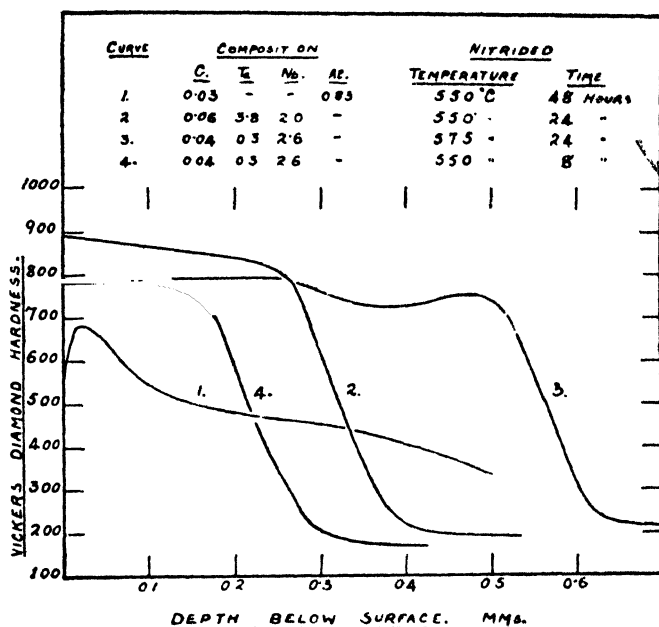


FIG. 148. PROPERTIES OF NITROGEN HARDENING STEELS CONTAINING NIOBIUM AND TANTALUM

the hardness and depth of the nitrided layer are clearly shown in Fig. 148* for the tantalum-niobium low carbon steels, whose compositions are given above the curves. Curve 1 relates to the steel containing no tantalum or niobium, the other three curves are for alloys containing these elements. It will be observed that in the case of Curve 3 the hardness is about 15 per cent greater and the depth of the hardened layer (Vickers diamond hardness 700) about 15 times that of the alloy of Curve 1.

When aluminium is present in tantalum-niobium steel, below 1 per cent, the hardness of the nitrided layer is increased, but its depth is reduced a little as compared with the alloy without aluminium. Thus

* "Tantalum and Niobium," R. Genders, D.Met., *Sands, Clays and Minerals Journal*, April, 1938.

in the instance of a nitriding low carbon steel containing 0.04 C, 0.27 Ta and 2.6 Nb (per cent) nitrided at 575° C. for 24 hours, the maximum hardness was about 790 (Vickers diamond hardness) and the depth of case down to 700 hardness 0.53 mm.

A steel of very similar composition but containing 0.85 per cent of aluminium when nitrided at 575° C. for 24 hours gave a maximum

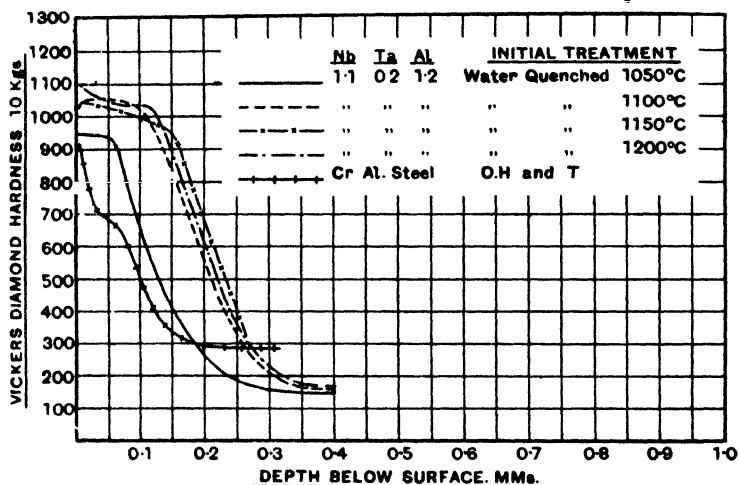


FIG. 149 PROPERTIES OF NITRIDING STEELS WITH NIOBIUM AND TANTALUM

hardness of over 1000 V.D.H. and a depth of case down to 700 hardness of 0.41 mm

In regard to the effect of the *initial quenching temperature* upon the hardness and depth of the nitrided layer in the case of 1 per cent niobium steel, the values shown graphically in Fig. 149 indicate that the hardness and depth of the nitrided layer are increased considerably for quenching temperatures of 1100 to 1200° C., as compared with 1050° C. In this connection the effect of the higher quenching temperature is to allow an increasing amount of niobium to be taken into solution.

Physical Properties of Nitralloy Steels

The specific gravity of the chromium-aluminium-molybdenum steel is about 7.75, whilst that of the non-aluminium Nitralloy steels usually lies between 7.82 and 7.87.

The thermal coefficient of expansion is slightly higher than for

ordinary steels. For aluminium content Nitralloy steels the value between 20 °C. and 500 °C. is 0.000014 and for non-aluminium ones about the same value. The coefficient of expansion of the nitrided case has been determined and found to be slightly less than that of the supporting core material, its value between 20 °C. and 500 °C. being 0.000013.

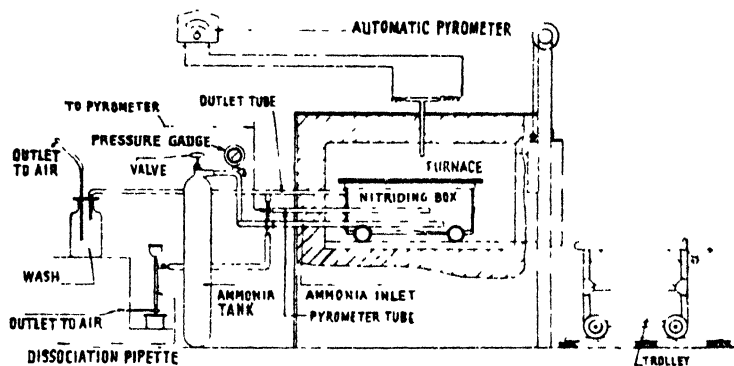


FIG. 150. SCHEMATIC LAY-OUT OF NITROGEN HARDENING PLANT

The electrical resistivity for 0.3 per cent carbon Nitralloy steel with 1.1 per cent aluminium is about 36 microhms per cm. cube. For the non-aluminium steels it lies between 22 and 28.

Nitriding Equipment

Fig. 150* shows the lay-out of a typical nitriding plant. It comprises a furnace provided with an automatic temperature control, a gas-tight container made of a high nickel-chromium steel (25 per cent Cr and 20 per cent Ni), which will not be attacked by the ammonia gas, a tank of ammonia provided with a suitable needle valve for controlling the flow of gas, inlet and outlet tubes, and finally a special pipette for determining the extent of the ammonia dissociation.

The ammonia tank must be placed in a position such that the bent tube inside the tank has its open end in the gaseous atmosphere and does not dip into the liquid ammonia. A suitable needle valve together with a pressure gauge ensures the control of a steady even flow of gas. The inlet and outlet tubes are made of nickel or aluminium, and the articles in the box should be supported on nickel grids. The inlet tube extends along the bottom of the box to the back, while the outlet

* "Hardening of Steel by the Nitrogen Process, H. W. Bowen, *Journ. Inst. Engrs.*, 1934 5.

tube is at the front end and near the top of the box. Pyrometers are inserted into both the container and the furnace. The furnace pyrometer is connected to the automatic control. The gas mixture from the container passes through a wash bottle to indicate the gas pressure (which is generally $\frac{1}{2}$ in. to 1 in. of water) as well as the rate of flow of the gas, and finally into the atmosphere or suitable drain.

Some of the ammonia gas decomposes into nitrogen and hydrogen according to the following chemical reaction—



As previously stated, the nitrides formed are in solid solution or in a fine state of dispersion in the case and impart extreme hardness to the steel. The products leaving the furnace consist of hydrogen, nitrogen and undissociated ammonia.

Parts of articles required to be kept soft are usually protected by tinning with a solder consisting of 4 parts of lead to 1 part of tin. A suitable flux consists of zinc dissolved in a mixture containing 500 c.c. hydrochloric acid, 250 c.c. water and 15 grams of sal ammoniac.

An alternative method is to dip the previously cleaned article in a bath of molten solder and then machine off the solder from the surfaces to be hardened. Special protective paints consisting of aluminium powder and sodium silicate can also be used for the soft areas. Any holes in the articles to be nitrided should be plugged with asbestos yarn and sealed with aluminium paint.

Manipulation and Applications

Nitralloy steels can be fabricated, e.g. forged, drop-stamped and hot pressed, in a similar manner to ordinary steels; as a rule parts can be finished machined or ground from rolled bars or forgings in the oil-hardened and tempered condition. The recommended forging temperatures are 1150° to 1200° C.; it is not advisable to work the steels below 850° C.

Nitralloy steels are much used for stampings and pressings; the latter should be normalized at 925° C. to 950° C., soaking at this temperature for a period depending upon the size or mass of the article.

Stampings for crankshafts and similar highly stressed parts should be normalized at 950° C. followed by oil-hardening at 930° C. and then tempered to give the required strength properties.

Nitralloy steels can be welded satisfactorily if certain precautions are taken. Thus, if the welded surface is to be nitrided afterwards, it is necessary to use a weld metal of Nitralloy composition. Electric arc welding is not recommended owing to the relatively heavy losses of

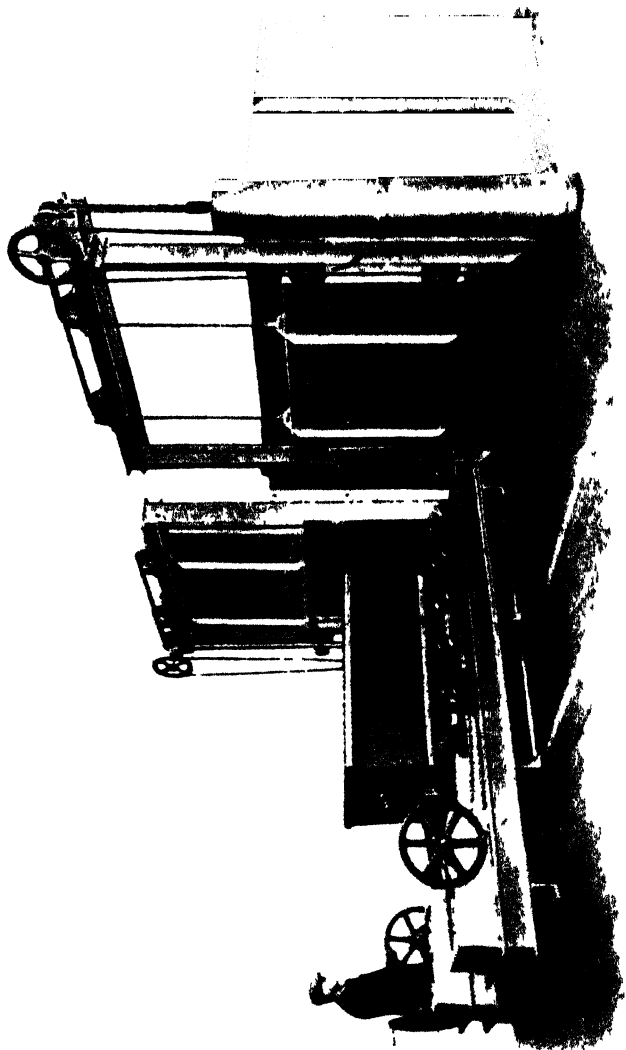


FIG. 151 TWO HORIZONTAL NITRIDING FURNACES WITH NITRIDING BOYS AND CHARGING BOYIE
(G.F. 144)



FIG. 152 A GROUP OF NITROGEN HARDENING FURNACES
(Sheepville St. Co. Centrifugal Castings Ltd.)

aluminium and chromium which alter the composition of the steel, thus making it unsuitable for subsequent nitriding. Electric resistance and oxy-acetylene welding give satisfactory results if certain precautions are taken, but the best results are obtained with the atomic hydrogen welding method.

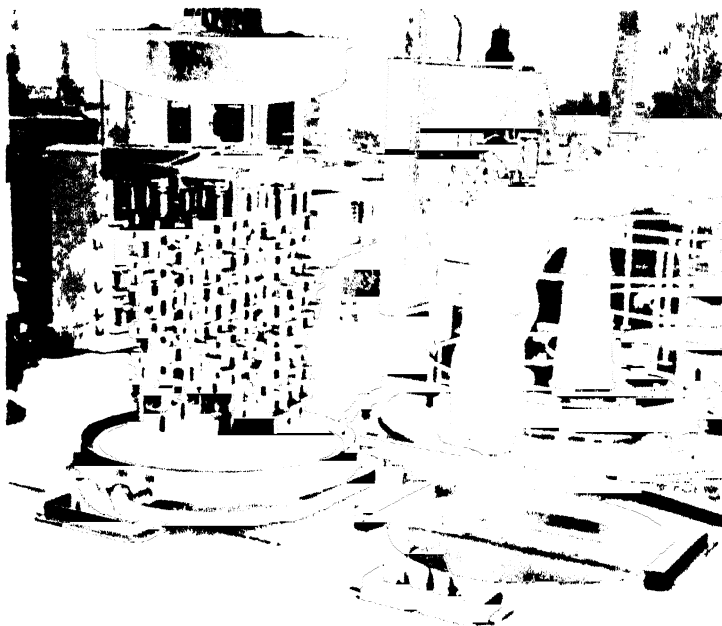


FIG. 153. PART OF AN INSTALLATION OF VERTICAL CYLINDRICAL ELECTRIC FURNACES FOR STABILIZING, TEMPERING, AND NITRIDING CRANKSHAFTS (G. F. C. Ltd.)

In regard to the subject of *machining Nitralloy steels*, as with other alloy steels, lower speeds than for ordinary carbon steels are imperative, whilst tools should be maintained in a sharp condition. In turning, a speed of 60 ft. per min. should not be greatly exceeded, and light finishing cuts will overcome any tendency of the material to drag. When cutting screw threads, each slope may be machined separately with as slow a finishing speed as conveniently possible.

In considering the tolerance to be worked to in machining, the following points should be kept in mind

1. Where parts have to be finished within very fine limits it is

desirable to grind or lap after nitriding, and allowance should be made accordingly when finishing before nitriding.

2. There is an increase on diameter of 0.001/0.002 in. on solid round bars, whilst on square and rectangular bars there is a similar growth amounting to about 0.0006 in. on the surface. In addition there is an increase in length which varies in accordance with the length of the article.

With hollow cylinders and rings there is, in addition to the surface growth, an expansion in the internal diameters which varies according to the diameter and wall thickness, and this is again affected when the bore or outside diameter is kept soft during nitriding; due allowance must therefore be made for these effects.

Nitralloy steels are now much used for aircraft and automobile engine crankshafts, for cylinder liners, pump spindles, shackle and steering pivot pins, brake drums, gudgeon pins, etc. Parts of machine tools, such as lathe, milling and grinding machine spindles, are sometimes made of Nitralloy steel. In the plastic moulding industry the steel is employed for moulds requiring maximum hardness and toughness. In locomotive engineering Nitralloy steels are used for gudgeon pins, motion link pins, link motion sliding parts, gears, pinions, pump shafts, etc.

Another application of these steels is in the mining and quarrying industry where parts have to work in dust-laden atmospheres, so that the maximum wear resistance is necessary for items such as spindles, pins, pump parts, elevator links, bushes, hammer parts, etc.

Nitrogen Hardening Cast Irons

These cast irons contain aluminium and chromium and are surface hardened by exposure at about 500 °C. to the action of anhydrous ammonia gas. The surface hardness thus obtained is of a high order and it is possible to obtain hardnesses of approximately 1000 without the aid of quenching processes. The alloy irons are known, collectively, as *Nitricastirons*, and they can be regarded as the cast iron equivalents of Nitralloy steels.

A typical percentage composition is as follows: Total C, 2.75; Si, 2.75; Mn, 0.75; S, 0.10; P, 0.10; Al, 1.75; Cr, 1.75.

When heated for a period varying from 40 to 90 hours at 500 °C. to 510 °C. and exposed to the action of a stream of dry ammonia gas the iron becomes case-hardened, yielding a Firth diamond hardness of 900 to 1000.

Its structure in the heat-treated condition shows a ground mass of pearlite in which the carbide is deposited in the form of small specks,

interspersed with large carbide areas and finely divided graphite, it is believed that the pearlite structure is similar to the so-called "spheroidized pearlite" characteristic of certain other high-duty cast irons.

The electric resistance furnace, with automatic temperature regulation, is suitable for hardening this iron, the machined castings being placed loosely in a gas-tight box without any packing material. The ammonia is maintained at a pressure of $\frac{1}{2}$ in. to 1 in. of water. It is noteworthy that no scaling or distortion occur in hardening this iron. Parts of castings which do not require to be hard can be protected with a special paint made up of powdered aluminum or chromic oxide and sodium silicate; this paint can be removed afterwards with boiling water.

Nitricastiron as compared with ordinary cast iron has a higher strength, a much higher modulus of elasticity, a lower permanent set value and greater intrinsic hardness, in the unhardened condition.

It develops its best strength and other qualities when centrifugally cast.

Table 92* shows the mechanical properties of Centrard Nitricast-irons of the percentage compositions given in Table 91

TABLE 91
COMPOSITIONS OF CENTRARD NITRICASTIRONS

	Total C	Gra- phite	Comb. C	Si	Mn	S	P	Cr	Al
A. Centrifugally cast	2.65	1.10	1.55	2.58	0.61	0.070	0.096	1.69	1.43
B. Sand cast	2.62	1.63	0.99	2.44	0.60	0.075	0.098	1.58	1.37

The permanent sets for the "as-cast" centrifugal and sand cast irons were 2.5 and 6.1 tons per sq. in., respectively. For the nitrogen-hardened irons the corresponding values were 4.75 and 9.7 tons per sq. in.

The specific gravity of Centrard iron is about 7.4.

The specific heat is 0.12 to 0.14 C.G.S. units

The coefficient of expansion from 30° to 100° C. is 1.09×10^{-5} ; for 100° to 200° C., 1.17×10^{-5} ; for 200° to 300° C., 1.35×10^{-5} ; and for 300° to 400° C., 1.5×10^{-5} .

* "Cast Iron Suitable for Nitrogen Hardening," J. E. Hurst, *Iron and Steel Industry*, November, 1933.

TABLE 92
MECHANICAL PROPERTIES OF CENTRARD NITRICASTIRON

Type	Condition	Modulus of Elasticity, Tons per sq. in.	Tensile Strength, Tons per sq. in.	Firth Diamond Hardness, 30 kg. Load
A	As cast	22.5	24.5	418
	Annealed	23.7	29.8	302
	Hardened and stabilized	23.0	29.5	302
	Nitrogen hardened	23.5	29.8	982
B	As cast	19.5	19.8	340
	Annealed	19.7	22.9	269
	Hardened and stabilized	19.2	28.6	300
	Nitrogen hardened	20.1	23.9	904

In regard to the *heat treatment* of this iron, in order to ensure uniform machining qualities the castings are annealed at 950° C., allowing them to cool slowly. They can be oil-hardened and tempered by quenching in oil from 870° C. and tempering at 600° C. to 700° C. The tempering treatment may be prolonged to give a stabilizing treatment for removing internal stresses. In cases where there is a risk of distortion *stabilizing treatment* should be carried out after preliminary rough machining operations by heating to 550° C. to 650° C. for 1 to 4 hours.

Nitricastiron has a much superior corrosion resistance to ordinary cast iron. It is used for cylinder liners of petrol and Diesel engines, valve parts, pump castings and machine tool parts requiring very hard wearing surfaces. It is also suitable for jigs, gauges, pulleys, wearing collars and bushes.

In regard to the wear resistance properties of Nitricastiron, some interesting figures were given by J. E. Hurst* on commercial vehicle and car engine cylinder liners. Stationary tests were carried out on a Leyland four-cylinder 4 in. bore petrol engine of standard type, on material in the form of cylinder liners of the type known as *dry liners*, while the road tests were carried out on a Riley six-cylinder car, and a Star six-cylinder car, the former with dry and the latter with wet liners. The results obtained are summarized in Table 93.

In connection with these results a strict comparison can be made only on the basis of equal mileages. At a mileage of 30,000 in the

* *Iron and Steel Institute Proc.*, 1933 4.

TABLE 93
AUTOMOBILE CYLINDER WEAR TESTS

Material	Total Mileage	Wear. Miles per 0.001 in.	Total Mileage	Wear. Miles per 0.001 in.
Stationary Engine Tests				
Centrifugally cast iron, standard to B.S.I. Spec. 4K6	30,000	12,000		
Chromium alloy cast iron, centri- fugally cast	30,000	9,250	40,000	12,300
Nitrogen hardened cast iron	30,000	24,000	40,000	32,000
Road Tests				
Centrifugally cast chromium cast iron, hardened and tempered			40,000	4,020
Centrifugally cast nickel chro- mium cast iron, hardened and tempered	10,000	3,220		
Nitrogen hardened cast iron	10,000	19,020	40,000	10,100

stationary engine tests, a comparison can be made between nitrogen-hardened cast iron, standard centrifugally cast and chromium alloy cast iron. At this mileage the ratio of the resistance to wear of nitrogen-hardened cast iron to standard centrifugally cast iron is as 2 : 1 and to chromium alloy cast iron as 2.6 : 1. At a mileage of 40,000, the ratio of the nitrogen-hardened to the chromium alloy cast iron still remains the same at 2.6 : 1.

In the tests under road conditions, the wear value in miles per 0.001 in. of wear is smaller in magnitude than under the stationary engine conditions, but at a mileage of 40,000 the ratio of the nitrogen-hardened to the hardened and tempered chromium alloy cast iron is 2.2 : 1, a figure which is in close agreement with the stationary engine tests.

Nitrogen-hardened Austenitic Cast Iron. The austenitic cast irons can now be nitrogen-hardened, the process used forming the subject of a patent.*

As is well known, certain austenitic cast irons possess a valuable property in that they have a high coefficient of expansion. This high coefficient of expansion renders the austenitic cast irons extremely valuable for use in conjunction with aluminium alloys and they are therefore the subject of much interest to the internal combustion engine designer desirous of utilizing aluminium alloys for the production of

* Sheepbridge Stokes Centrifugal Castings Co., Chesterfield.

cylinder castings. By treatment with the nitrogen-hardening process in accordance with the details of this new development, surface hardness of up to 500 Brinell can be obtained; it is anticipated that this process will have considerable influence in the extension of the use of these austenitic cast irons.

CHAPTER VIII

ELECTRICAL STEELS AND IRON ALLOYS

VARIOUS kinds of alloy steels and iron alloys (with nickel, cobalt, copper, etc.) are now widely used in electrical engineering work. These include magnetic and non-magnetic materials and alloys employed on account of their high electrical resistivity properties, etc.

Magnetic Materials

There are two principal classes of steel and iron alloys used on account of their magnetic properties, namely, (1) *magnetically soft*, and (2) *magnetically hard* materials. There is also another class of materials of approximate constant permeability over a wide range of magnetizing forces, these usually possess low remanence and coercivity and are used for purposes such as the continuous loading of submarine cables and in the cores of inductances for telephonic and radio circuits. They include iron-nickel-cobalt alloys, known as "Perminvars" and powdered materials for dust cores of telephone instruments, etc.; in this connection the carbonyl-nickel-iron powders are important instances.

The magnetically soft materials are those that are employed for purposes such as the cores of electromagnets and transformers, dynamo pole pieces, etc.

The magnetically hard materials are used for making permanent magnets. They include certain alloy steels of relatively great hardness, nickel-iron-aluminium alloys, and a number of special alloys.

In order to appreciate the magnetic properties of the magnetically soft steels (and irons), it is first necessary to appreciate the meanings of the terms employed, namely, *permeability*, *flux density*, *remanence* and *coercive force*, so that the following brief explanation of these terms is given.

The *permeability* of a material is a measure of its response to a magnetizing force and defines the magnetic value of the material, in reference to that of air which is taken as a standard. Thus if a coil of wire be wound around a circular section (closed) ring of soft iron and a current circulated around the coils, a certain number of magnetic lines of force would pass through the iron in the magnetic circuit. If the iron were replaced by air a much smaller number of magnetic lines would pass through the air inside the coil. The ratio of the number of lines of force in the iron to the number in the air "core"

is termed the permeability. In general the permeability is given by the following relation—

$$\mu = \frac{B}{H}$$

where B = the flux density (or number of magnetic lines per unit area) and H = the magnetizing force or the flux density produced in air, per unit area.

The value of μ for air is unity, whilst for magnetic materials such as iron, steel, nickel, cobalt and certain iron ores such as "magnetite," it is considerably greater than unity.

The magnetically soft materials give high permeability values and they are accordingly used for the cores of electromagnets, for dynamo pole pieces, transformer cores, etc.

Remanence is the term employed for the residual flux after the magnetizing force is reduced to zero. In the previous example of a current circulating in a coil wound around a ring of iron, if the current is cut off the magnetizing force becomes zero, but iron in common with other magnetic materials retains a certain residual magnetism. This property alone is not a measure of the usefulness of a material as a permanent magnet, since in the "zero" field condition the magnetic lines of force are in the closed circuit of the ring and have no outside effect.

If, however, the current is reversed in direction so as to give a demagnetizing action until the magnetism in the material is reduced to zero, the strength of the magnetic field, or the flux density, which just destroys the magnetism, is termed the *coercive force*. This force is a minimum for soft magnetic materials, e.g. iron, and a maximum for hard ones, e.g. alloy magnet steels. It is the coercive force that permits a bar magnet to retain its magnetism against the effect of its own poles and thus to store up magnetic energy and to provide an external magnetic field. In order to assess the value of a permanent magnet material it is usual to compare the product of the remanence and coercive force or, more accurately, maximum values of the product of B and H as defined previously, but with H as the reverse field flux and B the remaining induction: this gives an approximate measure of the magnetic energy that can be stored up in the material. It can be stated that remanence—which cannot be increased greatly—is relatively low for the newer magnetically hard materials, but the coercive force is much greater than for the earlier materials used for permanent magnets.

In the case of the more recent magnet steels these are made

short and thick, whereas formerly magnets were made long and thin in order to retain their magnetization against the reverse field of their poles.

Magnetically Soft Metals

The more widely used metals in this class are pure iron and silicon steel. It is necessary to reduce the carbon and oxygen in iron to a minimum since these elements have a powerful influence in lowering the permeability; other influences are those of *grain size* and *thermal treatment*.

The effect of carbon content on the permeability of steels is to lower the latter value as the carbon content is increased, i.e. the permeability diminishes with increase in hardness as the following results indicate -

Percentage of carbon	0.1	0.3	0.8	1.64
Maximum permeability μ	273	194	100	83

It is of interest to note* that exceedingly pure iron free from metallic impurities and gases has been prepared and has given the very high value of 210,000 for the permeability. This type of iron is not, however, a commercial proposition; where high permeabilities are required it is usual to employ nickel-iron alloys.

Other magnetically soft metals include Armco iron, vacuum-fused electrolytic iron, Stalloy, Hipernik and Permalloy, the two latter belong to the nickel-iron alloy group.

The mechanical and electrical properties of Armco and electrolytic iron have been referred to in Chapter I, so that it will here be necessary only to consider the magnetic properties.

The maximum permeability of Armco iron is given by Arnold and Elment as 7000. Its permeability for the value of the magnetizing force $H = 1$ (gilberts per centimetre) is 4300. It has a coercive force of 0.72 (gilberts per centimetre), and a hysteresis loss of 2100 ergs per cubic centimetre per cycle.

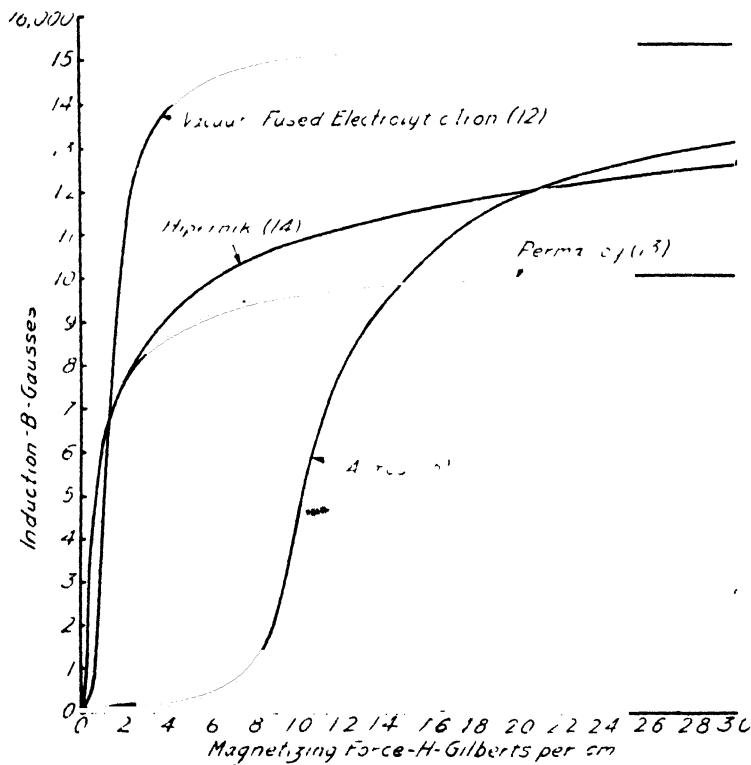
The magnetic properties of "iron" vary considerably with the grade, and in the past there has been a good deal of uncertainty and vagueness concerning the correct values of the magnetic constants to employ.

* "Recent Developments in Magnetic Materials," *Journ. Inst. Electr. Engrs.*, March, 1938.

† *Journ. Franklin Institute*, vol. cxcv, p. 621, 1923.

This uncertainty is shown by the fact that the value of the magnetic permeability has been given by various authorities as low as 25,000* and as high as 61,000.†

The differences are accounted for by the actual grades of iron employed for the experiments.



B-H curves for various materials.

FIG. 154 SHOWING PERMEABILITY VALUES OF FOUR MAGNETIC MATERIALS

Fig. 154 illustrates the permeability values of four important magnetic materials consisting of, or containing, iron. These are as follows—

- (1) Armco iron- the purest commercial grade of iron available.

* Rowland (1873) and Ewing (1885).

† Yensen and Ziegler (1928).

- (2) Vacuum-fused electrolytic iron.
- (3) Hipernik—a 50 per cent iron-nickel alloy.
- (4) Permalloy—a 78.5 per cent iron-nickel alloy.

The high permeability of the electrolytic iron at low magnetizing force values will be noted from Fig. 154, whilst the high permeability of Armeo iron for stronger magnetizing forces is a marked feature of this material.

The curves for vacuum-fused electrolytic iron represent about the best values hitherto obtained, and these high values are due, it is believed, to the reduction of the impurities, particularly carbon and oxygen.

The excellent magnetic values for Armeo iron render it particularly suitable for electrical purposes, as at high inductions its permeability approaches that of vacuum-fused electrolytic iron.

Nickel-Iron Magnetic Alloys. It has been found that nickel-iron alloys are excellent magnetically soft materials, and a study of these metals many years ago showed that suitably prepared and heat-treated alloys such as that containing 78.5 per cent nickel gave maximum permeabilities of 100,000 with low hysteresis loss. These alloys are to-day extensively used for such purposes as the loading of cables, for magnetic shielding, and in the construction of sensitive instruments and relays. They are also used in the cores of current transformers and in transformers and chokes for use in radio work. In all these applications high permeability and low losses are required at low field densities.

The nickel-iron alloys show certain disadvantages in their low saturation value, in their comparatively low electrical resistance, and the high degree of sensitivity of the magnetic properties to heat-treatment and mechanical work. This has led to the development of *ternary alloys* of improved properties in which the third element is usually *copper, chromium, molybdenum, or manganese*. The action of these elements is generally to lower still further the saturation values of the alloys, but on the other hand they increase the resistivity, stability and frequently the initial permeability.

Perhaps the most important series of these alloys is that formed by *nickel, iron, and copper*, and certain compositions in this series, coupled with suitable heat-treatment, have been found to offer remarkable combinations of properties (e.g. Mumetal).

Promising results have also been obtained by combinations of *iron and nickel* with *chromium or molybdenum*: the third element in these cases is effective in increasing resistivity and initial permeability, but the maximum permeability and saturation points of these alloys are substantially less than in the case of the 78 per cent nickel-iron.

Considerable attention has also been given to the more complex materials such, for example, as the nickel-iron-copper-molybdenum alloy known as "1040" with even higher initial permeability. Alloys of this type are of special value in radio and in the communications field generally.

One further interesting result may be mentioned, namely, the effect upon the *properties of nickel-iron alloys by cooling them in a magnetic field*. Thus, it was found that the 65 per cent nickel-iron alloy gave a maximum permeability of 600,000 after annealing in hydrogen for 18 hours and subsequently cooling in a magnetic field: at the same time the material showed further remarkable properties characterized by a hysteresis loop with vertical sides and square corners. The increased permeability is obtained only in the direction of the magnetic field and there is a corresponding loss in the direction at right-angles to this direction.

Yensen in America made a thorough study of the electrical and magnetic properties of iron-nickel alloys prepared by melting *in vacuo*. In Figs. 155 and 156 (the latter being taken from another source and including results of other investigators as well as those of Yensen) are reproduced some of his typical results. He found that the alloys containing approximately 50 per cent nickel could be forged and worked and that they had the following average electrical and magnetic properties which may be compared with those of pure iron and nickel—

Metal	Flux Density $H = 100$ Gausses	Saturation Value Gausses	Hysteresis Loss $B = 10,000$ ergs, cm ³ , cycle	Electrical Resistivity Microhm-cm
Pure iron	18,500	22,500	1,100	11
50 per cent alloy	15,500	15,500	800	45
Pure nickel	6,000	6,000	25,000	8

As the 50 per cent alloys are relatively incorrodible, they are of value under special conditions in the construction of electro-magnetic equipment. Another interesting magnetic characteristic of this alloy is the fact that the BH curve up to $B = 2000$ to 4000 gaussses is nearly linear, which makes it of value for certain electro-magnetic meters.

Fig. 155 shows the magnetic permeability of nickel-iron alloys melted and annealed in a vacuum for a value of $H = 100$ as obtained by Yensen.

Fig 156 gives corresponding electrical resistivity values for the same range of nickel-iron alloys

Permalloy This nickel iron alloy contains about 78 to 80 per cent

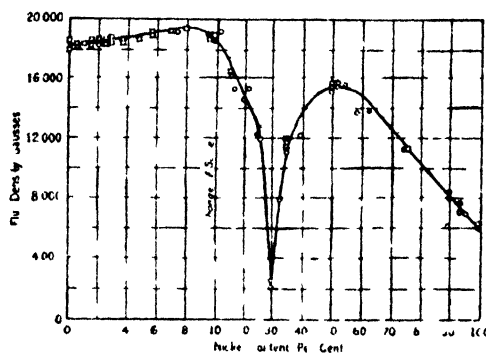


FIG 155 MAGNETIC PROPERTIES OF NICKEL IRON ALLOYS (FLUX DENSITY)

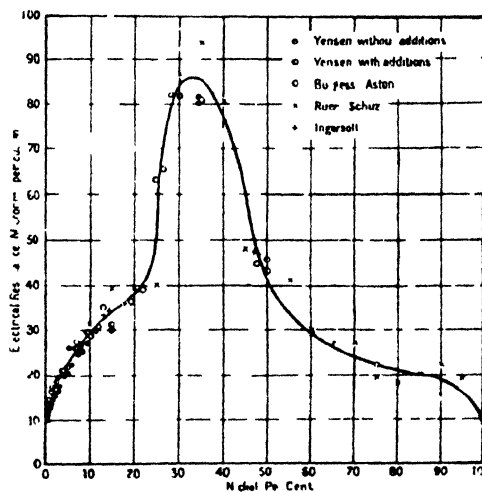


FIG 156 THE ELECTRICAL RESISTANCES OF NICKEL IRON ALLOYS

of nickel and has low carbon (0.04 per cent) silicon (0.03 per cent), manganese (0.22 per cent), with about 0.4 per cent of cobalt and 0.10 per cent of copper in a typical analysis. It was discovered by Arnold and Elmen of America.

This alloy has a high permeability at low inductions; it even approaches saturation in the earth's magnetic field. The initial permeability at zero field is about 13,000, i.e. about 30 times that of the best soft iron. The maximum permeability obtained is about 87,000, a value very much in excess of that for silicon steel. Tests have also shown that Permalloy possesses a greater magnetostriction than iron.

Permalloy and similar nickel-iron alloys are employed for ocean submarine cables and other purposes where very low magnetizations are involved. Its use for ocean cables has enabled the rate of sending messages to be increased from 300 to 1500 and more signals per minute.

Special Permalloys. More recently developed nickel-iron alloys, produced in the laboratories of the Bell Telephone Co. of America include the "45 Permalloy," "78 Permalloy" and "3·8—78 Chrome Permalloy."

The "45 Permalloy" has a resistivity nearly as high as silicon steel and a permeability at low or moderately high flux densities 2 or 3 times greater. Its coercive force is also considerably lower, but it is a more expensive metal. It is used largely in transformers and certain types of relays.

The "78 Permalloy" possesses a remarkably high permeability. Its initial and maximum permeabilities are more than 10 times those of silicon steel whilst its coercive force is only about one-tenth. Although its hysteresis loss is very low, its resistivity, namely, about one-third that of silicon steel, makes it less suitable than some of the other Permalloys for audio-frequency apparatus: it is used mainly for cores and armatures of sensitive relays.

The "3·8—78 Permalloy" was developed from the previous one by substituting about 4 per cent of chromium for the iron content of the latter. This metal has a resistivity somewhat higher than 4 per cent silicon steel and an initial permeability about 10 times as great, while its coercive force is only about one-tenth. Although expensive to produce it is being used in audio-frequency transformers and in some carrier frequency coils. In the form of a thin tape this alloy has been used for the continuous loading of a number of submarine telegraph cables.

Iron-Cobalt-Vanadium Alloy. In distinction to the Permalloys, the Bell Telephone Co. has developed a material which, unlike the Permalloys that saturate at relatively low flux densities, does not reach practical saturation until the flux density reaches 24,000 gauss. It consists of iron and cobalt in equal parts, with about 2 per cent of vanadium. Its initial permeability is 3 to 4 times that of magnetic

iron, while its maximum permeability is only about one-third as high; above a flux density of 12,000 gaussses its permeability is about 4 times that of magnetic iron. It is an expensive material but is finding an important application for the *pole tips of electromagnets*, producing highly concentrated magnetic forces.

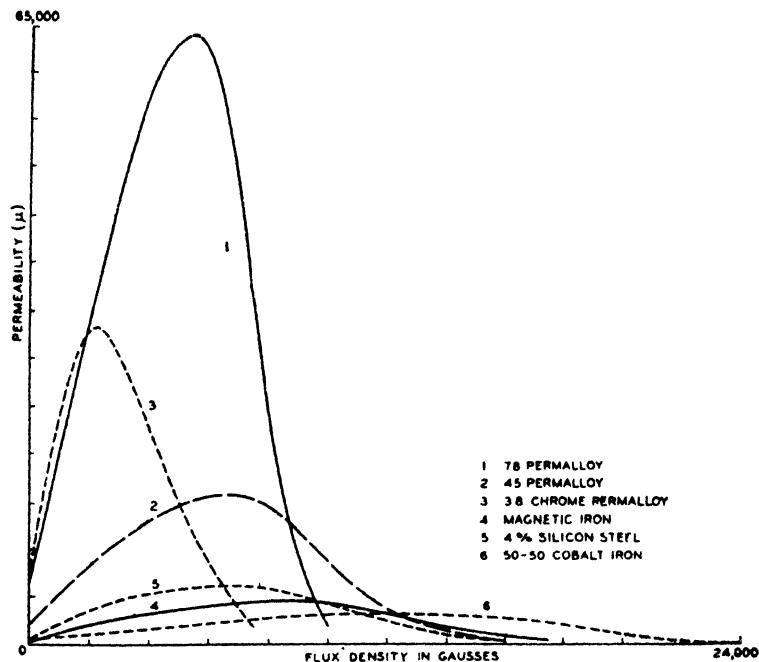


FIG. 157. MAGNETIC PROPERTIES OF PERMALLOYS AND OTHER METALS

Perminvar. This more recent alloy has somewhat remarkable magnetic qualities and includes iron nickel and cobalt alloys which when properly heat-treated are distinguished by their constancy of permeability over a region of flux density from zero to about one thousand gaussses. Since their permeability is substantially constant and their hysteresis loss small in this region, the Perminvars are superior to the Permalloys, and to the other magnetic materials previously discussed, in respect of the amount of distortion produced in transmitting speech currents. Hence the use of coils with Perminvar cores will result in distinctly superior transmission circuit characteristics. This is of especial importance in carrier systems. A Perminvar

which, over the region mentioned, exhibits great constancy in permeability contains 45 per cent nickel, 25 per cent cobalt, and 30 per cent iron. When properly heat-treated this Perminvar has a permeability of about 400: this value is sensibly constant up to a flux density of 1000 gauss. Other compositions have been found more desirable for specific purposes. For example, the Perminvar containing 70 per cent nickel, 7.5 per cent cobalt, and 22.5 per cent iron and designated "7.5-70 Perminvar" has a permeability of about 800 and its constancy is limited by specification so that its permeability increase must be less than 1 per cent over a range of flux density from zero to 500 gauss. One of the greatest drawbacks at present to the wide extension of the use of Perminvar is its permanent loss of the Perminvar characteristics if carried even momentarily to flux densities of only a few thousand gauss. Ordinary methods of demagnetization are only partially successful. Due to this characteristic and its high cost it has had application to only a few coils in which drastic reduction of modulation effects was demanded.

Silicon Steel. Silicon steel containing about 0.01 per cent carbon and 4 per cent silicon with very low manganese (0.03 to 0.05 per cent) in the annealed condition has a resistivity about five times that of magnetic iron, in consequence eddy currents are greatly decreased and this metal is suitable for the cores of apparatus operating within the audio-frequency range. It is used for the cores of transformers, armatures of dynamo and for telephone diaphragms, etc. Silicon steels of which Stalloy is an example, are available in sheet metal stampings and castings.

This steel has the advantage, also, of a considerably higher permeability than magnetic iron at the low flux densities which are usually produced in telephone apparatus operated by speech currents: it is, however, inferior to the "45 Permalloy" for the cores of audio-frequency apparatus.

Stalloy. A widely used steel for such parts as telephone and loud speaker diaphragms, and for electrical machinery, instruments, etc., where high permeability and low hysteresis and eddy current losses are concerned is an iron-silicon alloy, known as "Stalloy."

It contains from 3 to 4 per cent of silicon, and has higher permeability than iron for inductions below saturation. Its coercivity and retentivity are nearly 50 per cent lower than that of pure iron. It can be made with a total loss only slightly exceeding 1 watt per kilogramme when tested at 10,000 gauss maximum induction and 60 cycles per second, and a permeability of 8000 can be obtained.

TABLE 94
PROPERTIES OF ELECTRICAL SHEET STEELS

Material	Ordinary Dynamo and Motor Sheets	Special Dynamo and Motor Sheets	Transformer Sheets
	Low Open Hearth Carbon Steel	Low Open Hearth Carbon Steel	4 per Cent Silicon Low Carbon Steel
Specific gravity (sheet form)	7.79	7.72	7.5
Yield point, across grain, pounds per square inch	30,000	35,000	29,000
Tensile strength, across grain, pounds per square inch	48,000	52,000	96,000
Elongation in 8 inches, across grain, per cent	21	25	24
Yield point, along grain, pounds per square inch	33,000	38,000	22,000
Tensile strength, along grain, pounds per square inch	55,000	61,000	102,000
Elongation, along grain, per cent	22	19	24
Resistivity, microhm cm	8 to 12	15 to 18	40 to 50
Hysteresis loss at $B = 10,000$ ergs per cubic cm. per cycle	404.2	3.36	1790
Hysteresis coefficient	0.001609	0.001328	0.000715

Hard Magnetic Materials

The original steels used for permanent magnets were high carbon ones, heat-treated to give about maximum hardness values, such steels were subsequently replaced by tungsten steels containing about 0.5 per cent carbon and 5 to 6 per cent tungsten. The addition of 0.5 per cent chromium gives improved properties to such a steel. Thus, *a steel containing carbon (0.6), tungsten (5.5) and chromium (0.5)* when suitably hardened will give a coercive force of 65 to 75, a remanence of 10,000 to 11,000 and a maximum BH (product) of 250,000 to 300,000. This steel has been widely used for the permanent magnets for magnetos and telephone and meter magnets.

The steel requires special care in regard to its *heat-treatment* owing to the risk of distortion and cracking. In order to obtain satisfactory results it should be heated to 760 °C. and quenched in water. This condition gives the highest value for the coercive force. Any subsequent tempering results in a reduction of the coercive force; thus, if tempered at 300 °C. the coercive force falls to 25 to 30.

Chromium steel, containing about 1 per cent of carbon and 2 per cent of chromium, has also been widely used for permanent magnets. In the oil-hardened condition it has a coercive force of about 60, a remanence of about 8500, and a maximum BH (product) of about 230,000.

After a considerable amount of research work had been carried out on magnet steels it was found that the maximum BH (product

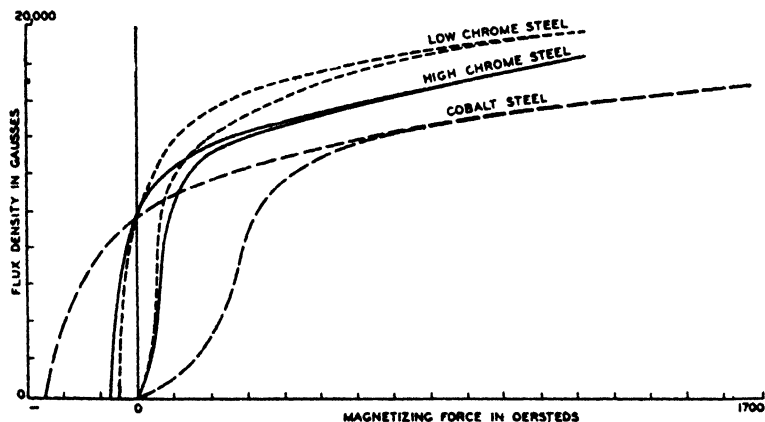


FIG. 158. CHARACTERISTIC CURVES OF MAGNET STEELS

was of great importance and special steels were developed for this result, and, incidentally, as previously mentioned, to enable shorter and thicker magnets to be employed.

The *cobalt-chrome steels* with cobalt content of 3 to 35 per cent were the next step in the development of permanent magnet steels, and although many difficulties were met with in regard to the hardening of these steels, they were subsequently overcome.

This type of magnet steel may be divided into two classes, namely, (1) the low and medium cobalt-chrome steels, and (2) the high cobalt ones.

The former class* includes one containing 9 per cent of cobalt with 9 to 10 per cent of chromium and another steel having 15 per cent of cobalt with 9 to 10 per cent of chromium. Both steels have about 1.15 per cent of carbon together with 1.5 per cent of molybdenum. These steels are air-hardening but for the best magnetic results a triple heat-treatment is necessary. This consists in an initial heating up to 1150° C. to 1200° C. for about 2 or 3 min., followed by cooling in air;

* "Cobalt Magnet Steels," H. E. Kershaw, *Proc. Sheffield Metall. Assoc.*, 1930.

this leaves the steel in the austenitic condition. Next, the steel is reheated to about 720 °C.; at about 680 °C. a marked recalescence occurs due to the breakdown of the austenite, with change to the magnetic condition. The steel is then allowed to cool in the air. The final heat-treatment consists in heating the steel to 1000 °C. fairly rapidly and after soaking at this temperature allowing it to cool in air.

The high cobalt steel, with 35 per cent of cobalt, 6 per cent chromium, 4 to 6 per cent of tungsten, and 0.9 per cent of carbon, is oil-hardened from 950 °C. This steel gives a maximum *BH* (product) of 900,000 to 1,000,000, the value being greater for thin sections and reaching a maximum of about 1,200,000.

Fig. 159* illustrates the magnetic properties of this group of cobalt chrome steels in comparison with chromium and tungsten ones, the values of *B* being shown plotted against *H*. The magnetic properties of the cast material are not so good as for the forged for the low and medium cobalt chrome steels, but in the case of the 35 per cent alloy it is possible to produce cast magnets having as good magnetic properties as forged ones.

Nickel Alloy Materials. In 1934, Mishima in Japan discovered a superior permanent magnet alloy containing about 2 parts of iron to 1 of nickel and 1 of aluminium, such that a small magnet of this material weighing only 2 oz. was capable of supporting a weight of 56 lb.

The *iron-nickel-aluminium* alloys, with or without cobalt, are at present the best materials yet discovered for permanent magnets.

The basic principle of these alloys is that the compound of nickel and aluminium forms a solid solution with iron at high temperatures and by suitable heat-treatment can be precipitated in a finely dispersed form.

The best results now appear to be obtained with 25 to 30 per cent of nickel and 10 to 15 per cent of aluminium, the balance being iron.

Table 95 shows the properties of two modern nickel-bearing alloys of this class, known as *Alni* and *Alnico*, in comparison with those of alternative magnet steels. The *Alnico* material, giving the highest *BH* max. results, has the following percentage composition: Ni, 18.0; Al, 10.0; Cu, 6.0; Co, 12, and the balance iron. the addition of copper has been made to give better control over the properties and heat-treatment.

Additional advantages of these two alloys are that they are less expensive than the alternative magnet steels and, being of low density, enable appreciable savings in weight and bulk to be effected.

* *Ibid.*, page 340.

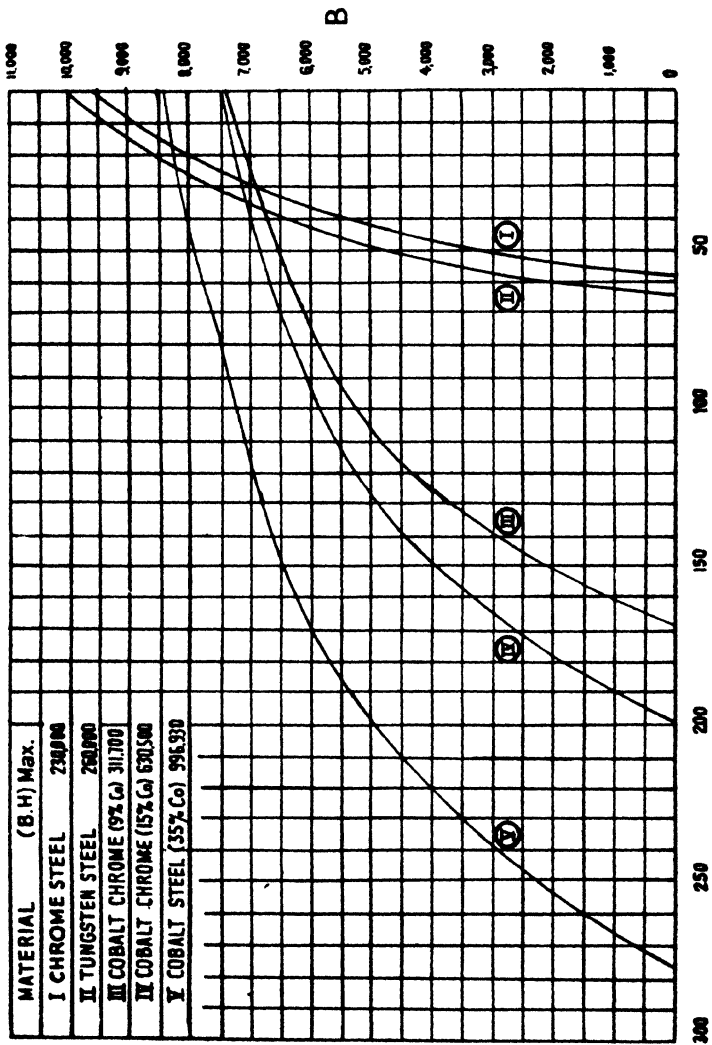


Fig 159. B H VALUES FOR TYPICAL Mn-Si STEELS

TABLE 95
PROPERTIES OF VARIOUS PERMANENT MAGNET MATERIALS

Material	Remanence	Coercive Force	BH max.
1% carbon steel	9,000	55	200,000
6% tungsten steel	11,000	67	300,000
3% chromium steel	9,000	65	250,000
15% Co-10% Cr steel	8,300	170	620,000
35% cobalt steel	9,600	250	1,000,000
Alni	6,300	500	1,250,000
Alnico	8,200	510	1,700,000

A nickel-iron-aluminium alloy, known as 'Nial' (Edgar Allen Ltd., Sheffield), now used for moving coil loud speaker magnets and other electrical generator types of magnet, has a *BH* (max.) value of 1,370,000, remanence of 5650 and coercive force of 610, being greatly superior to the 35 per cent cobalt alloy shown in Table 95.

It may be of interest to note that an alternative method of making up magnets from this series of alloys is by using the alloy in the form of a powder which is compressed in dies with bakelite or shellac as a binding medium, and heat-treated to obtain a solid mass. It is claimed that the coercive force of this type of magnet is only 5 to 10 per cent less than that of the solid alloy, the remanence being reduced by about 40 per cent. On the other hand the density of the powder material is also much less and its performance weight for weight is little inferior to that of the solid magnet of the same alloy.

The iron-nickel-aluminium and Alnico types of magnets as a result of their metallurgical structure do not suffer from ageing effects, and are also stable at elevated temperatures and under mechanical shock. An important result of this is that the alloy may successfully be used in welding operations.

Another development in permanent magnets has been the preparation of a series of alloys consisting of iron, nickel, cobalt and titanium, known as the "New K.S." alloys, and which show an even greater energy content than in the case of Alnico. The best composition has been found to be in the neighbourhood of 30 per cent cobalt, 16 per cent nickel and 12 per cent titanium. The production of these alloys is, however, expensive and the cost per unit of energy available is greater than for the iron-nickel-aluminium alloys; they have not, therefore, received much commercial attention.

Other developments have taken place in recent years in regard to

permanent magnetic alloys. Some of these are perhaps of more academic than practical interest; they include, for example, the production of magnets by sintering together iron oxide with cobalt ferrite (CoFe_2O_4). Among other alloys of scientific interest are the silver-manganese-aluminium alloys, and an alloy consisting of 93 per cent neodymium and 7 per cent iron which has the remarkably high coercive force of 4300. Alloys of platinum or palladium with iron or cobalt show similar high properties.

Magnetic Properties of Stainless Steels

Stainless steel, on account of its ability to resist rust and corrosion, has advantages over ordinary magnet steels for use in places exposed to sea-water, damp and corrosive atmospheres. It does not possess marked magnetic properties, but the 0.3 per cent carbon Firth stainless steel, when fully hardened by heating to 1000 °C. and quenching in water, provides a tolerably good material for permanent magnets in exposed places.

Table 96 gives the results of some magnetic determinations on Firth's stainless steels—

TABLE 96
MAGNETIC PROPERTIES OF STAINLESS STEELS

	Flux Density B for H 400	Maximum Per- meability	Coercive Force	Reman- ence
Stainless (0.3% C.) hard	12,500	75	58	6,500
Stainless (0.3% C.) soft	17,150	650	13	12,800
Stainless (0.1% C.) soft	17,170	500	7.5	6,100
"Stayblade" (Firth's)		31.5	15.5	550
S.80 stainless steel	14,300	210	19	6,400

Non-magnetic Steels

Alloy steels which during the heating or cooling stages from about 1000 to 1100 °C. show no arrest points, so that the solid solution or austenitic state is retained down to atmospheric temperatures, are non-magnetic. Typical examples of such steels are the 25 to 30 per cent nickel steel, certain stainless steels and 11 to 14 per cent manganese steel.

The Staybrite stainless steels are non-magnetic in the softened condition, but usually become slightly magnetic when cold-worked.

The permeabilities in fields of strength of $H = 50$ to 500 are 1.005 to 1.13 , the latter value corresponding to 10 per cent cold stretched F.S.T. Staybrite steel.

In connection with the high manganese steel previously mentioned the non-magnetic condition is obtained by heating to 950° to 1100° C. and quenching in water, so that the austenitic condition is thereby attained. When this steel is annealed it becomes hard, brittle and magnetic. Thus if this steel is soaked for relatively long periods for 40 to 60 hours at 450° C. and is cooled in air it becomes quite brittle and magnetic, having a permeability about one-half that of ordinary iron. If, however, the metal is reheated to 950° to 1100° C. and quenched in water, it regains its non-magnetic condition.

Another non magnetic steel is the nickel-manganese-chromium Firth "N.M.C." steel

Non-magnetic Cast Iron

Nomag, an austenitic cast iron produced by Ferranti Ltd. under the Ferranti-Dawson patents, is another non-magnetic material the properties of which are given in Chapter III.

Electrical Resistance Alloys

These alloys are characterized by their high electrical resistances and also by their marked resistances to corrosive influences at elevated temperatures. They are employed in the form of wire or tape for the heater elements of domestic electrical apparatus, such as electric cookers, boilers and irons, electric furnaces and rheostats employed for current control purposes, etc.

The alloys used include those of *nickel-copper*, *nickel-chromium*, *nickel-chromium-iron*, *nickel-copper-zinc*, *nickel manganese-copper*, *chromium-aluminium-iron*, etc.

The principal electrical properties and melting points of these alloys are given in Table 97.

The *nickel-copper-manganese* alloys containing 50 to 80 per cent manganese, 10 to 40 per cent nickel and 1 to 30 per cent copper have high resistivity, low thermo-electric force (with copper), good heat conductivity, permanence of electrical properties and are not sensitive to heat-treatment. The resistivities are high and vary from 18.8 to 22.0×10^{-5} ohms-cm. (or 188 to 220 microhms-cm.); these possess good ductility and tensile strength properties.

Another interesting alloy is that known as *Smith's No. 10 Alloy*, which contains about 37.5 per cent chromium, 7.5 per cent aluminium

TABLE 97

ELECTRIC RESISTANCE HEATING ELEMENTS*

Material	Composition	Specific Resistance (Ohm in 10)	Temperature Coefficient of Resistance per 100	Working Temperature	Remarks
Ferro	43-45% Ni 55-57% Cr	4.5	1.4	1200	Suitable for instrument shunts, arc resistances, low temperature heaters. It can be supplied with an oxide coating; this permits close spiralling with no further insulation.
Duralay	33-35% Ni 38-50% Cr Balance Fe	11	10	1400	Suitable for heater and arc resistances. Slight tendency to rust in damp place.
Glowray	65% Ni 15% Cr 20% Fe	10.5	20.2 20.56	1400	Withstand oxidation at moderately high temperatures. High resistance for limited spaces used in the higher grades of electric irons, soldering irons, tubular heaters, etc.
Brightay	50% Ni 20% Cr	10.5	9.5 (20.56)	1375	Ability to resist progressive oxidation and scaling at high temperatures. Suitable for furnace windings, electric fires and cookers, immersion heaters, etc.
Kanthal	An alloy containing Al (Cr)	41 14 13 13 all 20	12.5 12.40 11.6		Recommended for furnace use in sulphurous atmospheres. Specific resistance higher than Ni-Cr materials.
Platinum		1.5 (20)	80 (10.16)	1773	Non-oxidizing. Furnaces should not overrun specified temperature, owing to possible vaporization of the heater (Pt Resistance for temperatures up to 1400°C. Porcelain dental furnace windings).
Rhodum		0.47 (10)	44 (10.16)	1970	Permits high operating temperatures without the use of non-reducing gas atmospheres.
Molybdum		0.57 (20)	500 (10.14)	2555	Above 350°C. a non-reducing gas atmosphere must be used. Refractories should have good porosity thus permitting passage of the gas through the refractory walls.
Tungsten		0.55 (20)	110 (10.17)	3550	Working conditions similar to those for molybdenum.
Silic and Glow bar elements	Silicon carbide		1000 max. for useful life	Disintegrates 2200	Alkalies, alkali earths, heavy metal oxides, silicates and borates will cause destruction. Air and carbon dioxide oxidize silicon carbide. Water vapour affects the material. Hydrogen and fluorine with hydrogen content decompose the material.

Laboratory Electric Furnaces I. Walden, Furn. Sect. 1, 1910, n/a January

and 55 per cent iron. It has a resistivity about 80 per cent greater than *Nichrome** and can be used for temperatures up to 1350 C.; it is used for heater elements of high-speed steel and other electric furnaces.

A nickel-chromium alloy with specific resistance of 10.2 to 10.6 $\times 10^{-6}$ ohms-cm.

APPENDIX COMPOSITIONS, HEAT-TREATMENT

	Typical Analysis							Numl Specifi
	C	Si	Mn	Ni	Cr	V	Mo	
Carbon Steels	(1) 0.12	0.18	0.65	0.10				D 7 D 41 2 T 26 2 S 21 (See also D F D 141 12 A 2 S 14) 2 S 1 S 71 (See also 2 S 3 D I D 17 A) 2 S 6 S 76 S 70 S 79 D I D 153 W 3 S W 8 (See also D I D 215, 15
	(2) 0.28	0.20	0.75	0.22				
	(3) 0.41	0.44	0.90	0.42				
	(4) 0.50	0.23	0.80	0.16				
1½% Mangan	0.29	0.19	1.4	0.21				D I D 126 11 1 S 2 11 (See also 14 D I D 137 1 138
1% Nickel C H	(6) 0.12	0.1	0.0	3.10				3 S 13
34% Nickel	7 0.43	0.19	0.64	3.8	0.2			S 69
50% Nickel C H	(8) 0.12	0.14	0.30	4.1				2 S 4 S 67 (See also S 83 A)
3½% Nickel chromium	(9) 0.51	0.14	0.70	3.4	0.70			D I D 98 A 39 600 3 S 11 2 S 2 S 82 2 S 28 34 A 282
Nickel chromium C H	(10) 0.14	0.21	0.40	4.49	1.2			
Nickel chromium A H	(11) 0.28	0.15	0.60	4.20	1.5			
Ni, Cr, Mo, V	(12) 0.23	0.18	0.304	1.47	0.19	0.33	S 65 S 81	
Chromium molybdenum (13)	0.32	0.13	0.55		1.05	0.25	D I D 167	
Chromium molybdenum High tensile	(14) 0.30	0.21	0.59	0.89	0.88	0.94	D I D 228	
Carbon chrome	(15) 0.99	0.21	0.48	0.12	1.41			
Ball bearing steel								
Chrome vanadium	(16) 0.46	0.17	0.57	0.15	1.40	0.18	D I D 4 A	
Silicon manganese	(17) 0.52	1.95	1.05		0.05		D I D 115	
Chromium aluminum Steel for Nitriding	(18) 0.39	0.23	0.61		1.63	1.10	0.18 D I D 87	

* Courtesy, Dr. W. H. Hatfield

MECHANICAL PROPERTIES OF STRUCTURAL STEELS*

Treatment or Condition	Mechanical Properties							Fatigue Limit ¹ in S _N	Modulus of Elasticity ² in tons sq. in.
	Yield Point ³ in tons sq. in.	Tensile Strength ⁴ in tons sq. in.	Max. Strain ⁵ in %	Elongation ⁶ in 1 in.	R _A ⁷ in %	Brinell ⁸	Impact ⁹		
annealed 900 °C	16.2-17.5	28.5-37	64.5-65	124	13	13400			
rolled W Q 760 °C	14.1-17.2	31.5-35	60.9-85	137	14.0	13400			
annealed 870 °C	18.5-19.5	34.8-36.5	57.0-62	151	14.5	13400			
annealed 850 °C	10.8-23.1	38.0-42	36-28	170	16.5	13400			
annealed 1830 °C	10.2-7.8	46-41	38.0-10	202	19.0	13500			
oil harden 850 °C	20.5-21.0	30.0-48	55.0-12	11	22.5	13150			
temp 600 °C									
annealed 850 °C	20.5-24.6	40-30.0	57.0-50	187	17.5	13400			
oil harden 850 °C	24.0-24.1	40-40	59.0-85	187	17.5	13400			
temp 640 °C									
rolled W Q 760 °C	26.0-35.4	44.3-50.0	11.0-70	217	20.5	13050			
oil quenched 850 °C	33.0-36.4	63.8-65.0	11.0-55	293	27.0	13050			
temp 570 °C									
rolled 840 °C	39.40.1	58.8-48.0	48.0-28	269	25.0	13000			
W Q 760 °C									
oil harden 820 °C	50.0-54.5	60.1-62.0	61.0-68	277	26.5	13100			
temp 600 °C									
rolled oil Q 760 °C	48.3-70.3	89.0-18.0	63.7-30	418	34.0	13100			
oil harden 820 °C	65.2-85.0	106.0-12	45.0-15	49	45.0	13150			
temp 250 °C									
oil Q 850 °C	65.1-98.7	73.9-21.5	65.0-48	340	52.0	11200			
temp 640 °C A C									
oil harden 820 °C	36.5-45.5	53.8-24.5	67.0-65	255	22.0	13150			
temp 680 °C									
oil Q 875 °C	53.7-58.5	64.0-19.0	57.0-50	293	27.0	13150			
temp 640 °C A C									
W H 810									
oil Q 850 °C	72.0-82.5	87.0-16.0	48.0-24	402	50	13000			
temp 490 °C									
oil harden 860 °C	66.0-78.5	90.2-14.0	32.0-11	418	43.0	12500			
temp 480 °C									
oil harden 900 °C	47.6-50.2	57.5-22.5	59-50	289	24.9	12800			
temp 650 °C									

APPENDIX

PHYSICAL PROPERTIES OF STRUCTURAL

		Typical Analysis						
		C	Si	Mn	Ni	Cr	V	N
Carbon Steels	(1)	0.12	0.18	0.65	0.10	—	—	—
	(2)	0.28	0.20	0.75	0.22	—	—	—
	(3)	0.41	0.14	0.50	0.12	—	—	—
	(4)	0.55	0.23	0.58	0.16	—	—	—
1½% Manganese	(5)	0.29	0.19	1.4	0.21	—	—	—
3% Nickel C H	(6)	0.12	0.15	0.50	3.10	—	—	—
3½% Nickel	(7)	0.43	0.19	0.64	3.58	0.2	—	—
5% Nickel C H	(8)	0.12	0.14	0.30	4.9	—	—	—
3½% Nickel chromium	(9)	0.31	0.14	0.70	3.4	0.70	—	—
Nickel chromium C H	(10)	0.14	0.21	0.40	4.49	1.2	—	—
Nickel chromium A H	(11)	0.28	0.15	0.50	4.20	1.5	—	—
Ni Cr Mo, V	(12)	0.23	0.18	0.55	3.04	1.47	0.19	0.53
Chromium molybdenum	(13)	0.32	0.13	0.55	—	1.05	—	0.25
Chromium molybdenum High tensile	(14)	0.30	0.21	0.59	0.89	0.88	—	0.94
Carbon chrome Ball bearing Steel	(15)	0.99	0.21	0.48	0.12	1.41	—	—
Chrome vanadium	(16)	0.46	0.17	0.57	0.15	1.40	0.18	—
Silicon manganese	(17)	0.52	1.95	1.05	—	0.05	—	—
Chrome aluminum Steel for Nitriding	(18)	0.39	0.23	0.61	—	1.63	Al 1.10	0.18

No. II

STEELS GIVEN IN APPENDIX I

Physical Properties						
Specific Gravity	Thermal Expansivity Parts per Million	Thermal Conductivity	Electrical Resistivity Mic per cm	Weldability	Air-hardening Characteristics	Magnetic Properties
7 87	13 0	0 12	15	Good	None	High permeability
7 86	12 7	0 112	18	F good	None	Good permeability
7 85	12 7	0 110	19	Moderate	None	Good permeability
7 83	12 6	0 092	21	Moderate	None	Magnetic
7 86	12 7	0 087	21 5	Good	Slight	Magnetic
7 88	12 5	0 095	21 5	Good	Present	Magnetic
7 87	12 5	0 080	26 0	Moderate	Present	Magnetic
7 87	12 4	0 075	25 5	Moderate	Present	Magnetic
7 87	12 7	0 080	25 0	Moderate	Present	Magnetic
7 87	13 0	0 070	23 0	Moderate	Marked	Magnetic
7 87	12 7	0 070	27 0	Moderate	Strong	Magnetic
7 86	12 7	0 070	24 5	Moderate	Marked	Magnetic
7 84	12 6	0 095	22 0	F good	Present	Magnetic
7 86	12 5	0 070	23 0	Moderate	Present	Magnetic
7 81	12 2					Magnetic
7 83	12 6	0 110	23 0	Moderate	Present	Magnetic
7 73	12 5	0 045	45 0	Moderate	Present	Magnetic
3	(Case 11 8) 13 0	0 05	39 0	Moderate	Present	Magnetic

APPENDIX

COMPOSITIONS, HEAT-TREATMENTS AND MECHANICAL PROPERTIES

Steel	Analysis							Number of Specifications
	C	Si	Mn	Ni	Cr	V	Mo	
19. Stainless Iron Bar	0.08	0.10	0.12	0.15	13.5	—	—	D.T.D. 39, 53, 23 B. 97, 161 (See also 158) S.61, D.T.D. 10
20. Stainless Iron Tubes	0.10	0.21	0.32	0.18	13.6	—	—	D.T.D. 105
21. Stainless Iron Tubes	0.11	0.11	0.33	0.21	13.7	—	—	D.T.D. 46A, 19
22. Stainless Iron Strip	0.18	0.29	0.31	0.22	13.85	—	—	S.62
23. High - chromium, low-nickel	0.27	0.35	0.26	0.29	13.1	—	—	D.T.D. 146
24. High - chromium, low-nickel	0.11	0.13	0.15	1.9	17.9	—	—	185 A (See also 225) D.T.D. 60A 163, S.80 and 199 D.T.D. 168
25. Austenitic Stainless Cr, Ni Steels	0.12	0.29	0.15	2.75	17.7	—	—	171A 176A 207A 189
	0.11	0.52	0.29	8.1	18.2	W 0.61	T ₁ 0.65	166A 211 181
	0.12	0.35	0.30	8.05	17.9	W 0.63	T ₁ 0.69	2.05 W 3.16
26. { Cr, Ni, W Valve	0.44	1.1	0.71	14.1	14.0	—	—	D.T.D. 49A
27. { Cr, Ni, W Valve	0.34	1.39	0.46	10.95	21.39	—	—	D.T.D. 49A
	0.42	1.42	0.12	20.7	23.5	—	—	2.8 W 3.2
28. Silicon-chromium Valve Steel	0.41	1.75	0.92	28.5	14.4	—	—	D.T.D. 13B
29. 14% W High-speed Steel	0.44	3.9	0.52	0.15	8.1	—	—	W 14.5 S.68
30. Nickel-manganese-chrome (High-expansion Steel)	0.61	0.25	0.30	0.1	3.9	0.7	—	—
31. 12% Mn Steel for Castings	0.59	0.30	5.1	11.9	3.4	—	—	D.T.D. 93
	1.1	0.5	11.9	—	—	—	—	—

* Courtesy Dr. W. H. Hatfield

o. III

PROPERTIES OF RICH ALLOY STEELS FOR SPECIAL PURPOSES*

Treatment or Condition	Mechanical Properties								
	0.1% Proof tons/sq. in.	Yield Point tons/sq. in.	Max. Stress tons/sq. in.	Elongation per cent	R A per cent	Tensile	Brinell	Fatigue Range	Modulus of Elasticity tons/sq. in.
A.C. 950. T.750° C. A.C.	20.0	24.0	33.9	32.0	72	80	163	14.0	13400
O.H. 940. T.700° C. or C. drawn and T	24.0	31.0	40.8	29.0	71	90	196	17.5	13400
O.H. 950. T.550° C.	37.0	43.5	55.2	19.0	57	45	262	24.5	13400
A.H. 1000° C. T.150° C.	67.8	76.5	83.4	7.0			380	43	13400
O.H. 940° C. T.700 W.Q.	34.0	38.5	50.2	25	61.5	50	241	21.0	13700
Sheet softened 670° C.	31.0	34.0	41.8	19			202		13500
O.H. 960. T.520 W.Q.	39.0	42.7	56.8	19.5	55.8	45	209	23.5	13500
O.H. 950. T	64.1	71.1	80.4	8.0			377		13500
A.C. 1050° C.	15.3	17.5	42.9	60	62	100	175	17.5	12900
C.R. sheet and strip Tubes Wire ropes	45	50.8	66	18					12500
Valves A.C. 950° C.		39	54.6	39.5	47.5	38	255	20	13000
Valves A.C. 950° C.	20	38	57	25.2	35	40	269	21	13000
valves A.C. 950° C.	20	38	54	26.0	34	42	255	20.5	13000
Valves W.Q. 1000° C.	—	36.9	48.5	38	46	49	235	—	13000
O.Q. 950. T.700° C.	45	53.2	66.2	16	32	low	290	24	12500
Annealed	20.8	28.3	31.6	16.6	27.5	low	241	18	14500
Forged	20.5	32.5	56.2	38	48	90	295	22	13200
A.C. 1050° C.	15.2	21	42	50	60	110	185	19	13200
W.Q. 1000° C.	—	—	—	—	—	—	210	—	—

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APPENDIX

PHYSICAL PROPERTIES OF THE RICH ALLOY STEELS

Steel	Analysis						W
	C	Si	Mn	Ni	Cr	V	
19. Stainless Iron Bar . . .	0.08	0.10	0.12	0.15	13.5	—	—
20. Stainless Iron Tubes . . .	0.10	0.21	0.32	0.18	13.6	—	—
Stainless Iron Tubes . . .	0.11	0.11	0.33	0.21	13.7	—	—
21. Stainless Iron Strip . . .	0.18	0.29	0.31	0.22	13.85	—	—
22. Stainless Steel Bar . . .	0.27	0.35	0.26	0.29	13.1	—	—
23. High Cr, low Ni . . .	0.11	0.13	0.15	1.9	17.9	—	—
24. High Cr, low Ni . . .	0.12	0.29	0.15	2.75	17.7	—	—
High Cr, low Ni . . .	0.12	0.30	0.23	2.46	18.32	—	—
25. Austenitic Stainless Cr, Ni Steels . . .	0.11	0.52	0.29	8.1	18.2	W 0.61	1.1 0.6
	0.12	0.55	0.30	8.05	17.9	W 0.63	1.1 0.6
26. { Cr, Ni, W Valve . . .	0.44	1.10	0.71	14.1	14.0	—	W 2.05
{ Cr, Ni, W Valve . . .	0.34	1.39	0.46	10.95	21.39	—	W 3.16
27. { Cr, Ni, W Valve . . .	0.42	1.42	0.12	20.7	23.5	—	W 2.8
{ Cr, Ni, W Valve . . .	0.41	1.75	0.92	28.5	14.4	—	W 3.2
28. Silicon-chrome Valve Steel .	0.44	3.90	0.52	0.15	8.1	—	—
29. 14% W High-speed Steel .	0.61	0.25	0.30	0.1	3.9	0.7	W 14.5
30. Nickel-manganese-chrome (High-expansion Steel) .	0.59	0.30	5.10	11.9	3.4	—	—
31. 12% Manganese Steel for Castings . . .	1.10	0.50	11.9	—	—	—	—

No. IV

FOR SPECIAL PURPOSES GIVEN IN APPENDIX III

Physical Properties						
Specific Gravity	Thermal Expansion 0-300 Parts per Million	Thermal Conductivity	Electrical Resistivity	Welding Characteristic	Air-hardening Properties	Magnetic Properties
7.725	11.3	0.045	55	Moderate	Very slight	High permeability
7.725	11.3	0.045	55	Moderate	Very slight	High permeability
7.725	11.3	0.045	55	Moderate	Very slight	High permeability
7.725	11.3	0.045	57	Moderate	Not very marked	Magnetic
7.738	11.2	0.044	60	Less good	Notable	Magnetic
7.731	11.3	0.038	73	Less good	Notable	Magnetic
7.731	11.3	0.038	75	Less good	Notable	Magnetic
7.731	11.3	0.038	75	Less good	Notable	Magnetic
7.905	17.5	0.33	74	Good	None	Non-magnetic
7.905	17.5	0.33	74	Good	None	Non-magnetic
7.92	17.2	0.032	80	Moderate	None	Non-magnetic
7.90	15.9	0.027	87	Moderate	None	Non-magnetic
7.70	16.7	0.031	92	Moderate	None	Non-magnetic
8.0	16.3	0.030	92	Moderate	None	Non-magnetic
7.6	12.9	0.030	80	Poor	Marked	Magnetic
8.55	11.3	0.025	65	Poor	Marked	Magnetic
7.90	22.2	0.025	74	Moderate	None	Non-magnetic
7.88	19.0	0.028	70	F. good	None	Non-magnetic

APPENDIX No. V

BRITISH STANDARD SPECIFICATIONS FOR METALS AND ALLOYS (ABRIDGED)*

I. FERROUS MATERIALS, ETC.

- 32 1935. Steel Bars for the Production of Machined Parts for General Engineering Purposes.
- 51 1939. Wrought Iron for General Engineering Purposes (Grades A, B and C). [*Add.* November, 1939.]
- 224 1938. Steel for Die Blocks for Drop Forgings.
- 309 1927. White Heart Malleable Iron Castings. [*Add.* May, 1931.]
- 310 1927. Black Heart Malleable Iron Castings. [*Add.* May, 1931.]
- 321 1938. General Grey Iron Castings, Grades A and C.
- 592-1935. Steel Castings for General Engineering Purposes. [*Add.* February, 1941.]
- 681 1936. Carbon Chromium Steel.
- 682 1936. 3 per cent Nickel-chromium Case-hardening Steel.
- 725 1937. Hot Rolled Mild Steel Strip (or Hoop) not exceeding 10 inches wide for General Engineering Purposes.
- 762 1938. Wrought Iron Bars, "Special" Grade.
- 786 1938. High Duty Iron Castings, Grades 1, 2 and 3.
- 821 1938. Iron Castings for Gears and Gear Blanks (Ordinary, Medium and High Grade).
- 847 1939. Cold Rolled Mild Steel Strip for General Engineering Purposes.
- 858 1939. "Best Yorkshire" Wrought Iron. [*Add.* October, 1940.]
- 1 1920. Rolled Steel Sections for Structural Purposes. [*Under Revision*, 1940.]
- 13 1910. Steel for Shipbuilding, Structural. [*Under Revision*, 1940.]
- 18 1938. Tensile Testing of Metals.
- 182-184- 1938. Galvanized Iron and Steel Wire.
- 399-400 - 1930 1. High and Low Carbon Steel Cylinders for Storage of Permanent Gases.
- 449- 1937. Use of Structural Steel in Building. [*Add.* November, 1939.]
- 485 - 1931. Tests on Thin Sheet Metal and Strip [not exceeding 0.128 inch].
- 494 - 1933. Cold Drawn Weldless Steel Tubes for Steel Boilers and Superheaters.
- 499 - 1939. Welding and Cutting, Nomenclature, Definitions and Symbols for.
- 512- 1931. Hot Finished Weldless Steel Boiler and Superheater Tubes [for Temperatures exceeding 850° Fah.].
- 528-1934. Lapwelded Steel Boiler Tubes for External Pressure.
- 548-1934. High Tensile Structural Steel for Bridges, etc. [*Add.* May, 1936, and February, 1938.]
- 560-1934. Engineering Symbols and Abbreviations. British Standard.
- 601-1935. Steel Sheets for Transformers for Power and Lighting.
- 621-1935. Wire Ropes of Special Construction for Engineering Purposes.

* British Standards Institution, 28 Victoria Street, London, S.W.1.

- 640—1935. Bare Rod or Wire Electrodes for Metal Arc Welding. Wrought Iron and Mild Steel.
- 641—1935. Small Rivets (Ferrous and Non-ferrous) for General Purposes.
- 693—1936. Oxy-acetylene Welding as Applied to Steel Structures.
- 933—1941. Magnetic Materials for Use under Combined D.C. and A.C. Magnetization.
- 968—1941. High Tensile (Fusion Welding Quality) Structural Steel for Bridges, etc., and General Building Construction.

II. AUTOMOBILE MATERIALS AND PARTS

- 5001—1924; 5002 1924; 5003 1927. *Cancelled.*
- 5004—1927. Cast Iron Piston Ring Pots (Sand Cast and Chill Cast) for Automobiles.
- 5005 1924. Wrought Steels for Automobiles. [*Add.* June, 1929.]
- 5006 1924. Cold Worked Steel Bars and Strip for Automobiles. [*Add.* June, 1928.]
- 5007—1924. Sheet Steels for Automobiles.
- 5008—1924. Valve Steels and Valve Forgings for Automobiles.
- 5009 1924. Steel Tubes for Automobiles.
- 5010 1925. Steels for Laminated Springs for Automobiles
- 5015—1927. Splines (Bottom Fitting) for Automobiles. Dimensions for. [*Under Revision.*]
- 5016—1923; 5017 1923; 5018 1923; 5019 1923; 5020 1924; 5021 1928. *Cancelled.*
- 5027—1924. Magnefos for Internal Combustion Engines. Dimensions for.
- 5028—1924. Steel Castings (Nos. 1 and 2 Grade) for Automobiles.

III. NON-FERROUS MATERIALS, ETC.

- 359—1929. 98 per cent Aluminium (Notched Bars, Ingots, Rolling Slabs and Billets).
- 360—1929. 99 per cent Aluminium (Notched Bars and Ingots).
- 361—1929. 7 per cent Copper-aluminium Alloy Castings for General Engineering Purposes.
- 362—1929. 12 per cent Copper-aluminium Alloy Castings for General Engineering Purposes.
- 363—1929. Zinc-copper-aluminium Alloy Castings (Crank Cases and General Use).
- 385—1930. Pure Aluminium Tubes for General Engineering Purposes.
- 386—1930. Pure Aluminium Bars and Sections for General Engineering Purposes.
- 388—1938. Aluminium (Powder and Paste) for Paints.
- 395—1930. Wrought Light Aluminium Alloy (Duralumin) Sheets and Strips for General Engineering Purposes.
- 396—1930. Wrought Light Aluminium Alloy (Duralumin) Tubes for General Engineering Purposes.
- 414—1931. Wrought Light Aluminium Alloy Sheets and Strip (Heat-treated) for General Engineering Purposes. [*Covering Y-alloy, also.*]
- 477—1933. Wrought Light Aluminium Alloy Bars for General Engineering Purposes. [*Covering Duralumin.*]
- 478—1933. Wrought Y-alloy Bars for General Engineering Purposes.

- 532—1934. Light Aluminium Alloy Forgings for General Engineering Purposes. [Covering Duralumin.]
- 533—1934. Y-alloy Forgings for General Engineering Purposes.
- 702—1936. Silicon Aluminium Alloy Castings for General Engineering Purposes.
- 703—1936. Y-alloy Castings (as Cast) for General Engineering Purposes.
- 704—1926. Y-alloy Castings (Heat-treated) for General Engineering Purposes.
- 918—1940. Aluminium Bars Containing Small Proportions of Copper and Zinc for General Engineering Purposes.
- 24—Part 5 1925. Railway Rolling Stock. Copper Plates, Rods, Tubes and Pipes and Brass Tubes.
- 99 1922. Copper Alloy Pipe Fittings. Screwed for Low and Medium Pressure B.S. Copper Tubes. [Add. October, 1927.]
- 61 1913. Copper Tubes and their Screwed Threads. (Domestic and Similar Work.)
- 125—1930. Hard Drawn Copper Solid and Stranded Circular Conductors for Overhead Power Transmission Purposes. [Add. November, 1933.]
- 128—1929. Bare Annealed Copper Wire for Electrical Machinery and Apparatus. Dimensions and Resistances. [Add. April, 1930, and November, 1935.]
- 174 181 1938. Overhead Line Material [Non-ferrous] for Telegraph and Telephone Purposes. [Includes Copper, Bronze and Copper-cadmium Wires.]
- 198 1925. Electrolytic Copper Wire Bars, Cakes, Slabs and Billets.
- 199 1924. Electrolytic Copper Ingots and Copper Bars.
- 200 1921. Tough Copper Cakes and Billets for Rolling.
- 201 1921. Fine Copper Cakes for Rolling.
- 202 1924. Electrolytic Cathode Copper.
- 203 1924. "Best Select" Copper.
- 207 1921. Special Brass Ingots for Castings.
- 208 1924. Special Brass Castings.
- 218 1925. Brass Bars and Sections, suitable for Forgings and Drop Forgings.
- 249 1926. Brass Bars (High Speed Screwing and Turning). [Add. February, 1931, and November, 1932.]
- 250 1926. Brass Bars, High Tensile, and Sections (Grades A and B). [Add. November, 1932.]
- 251 1927. Naval Brass (Admiralty Mixture) Bars and Sections. [Add. July, 1931, and November, 1932.]
- 252—1927. Naval Brass (Special Mixture) Bars and Sections. [Add. November, 1932. —Under Revision.]
- 265—1936. Cold Rolled Brass Sheets, Strip and Foil (Copper, 61.5 per cent to 64.0 per cent).
- 266 —1936. Cold Rolled Brass Sheets, Strip and Foil (Copper, 64.0 per cent to 67.0 per cent).
- 267 —1936. Cold Rolled Brass Sheets, Strip and Foil (Copper, 68.0 per cent to 72.0 per cent).
- 352—1929. Phosphor Bronze Turbine Blading.
- 356 1929. Brass Armouring Wire for Electrical Cables.
- 369—1929. Phosphor Bronze Bars or Rods for General Purposes (Grades A and B).

- 378--1930. Brass Tubes and Screwed Glands for Condensers for Land Purposes.
- 382--1930. 2 10 88 Bronze (Gun-metal) Ingots for General Engineering Purposes.
- 382--1930. 2 10 88 Bronze (Gun-metal) Castings for General Engineering Purposes.
- 384--1930. Hard Drawn Phosphor Bronze Wire, Primarily for Armature Binding.
- 407 1939. Phosphor Bronze Sheets, Strip and Foil (up to 10 S.W.G.).
- 409- 1931 Naval Brass Plates, Sheets and Strips. (Excluding N.B. Condenser Plates.)
- 421 1931. Phosphor Bronze Castings for Gear Blanks.
- 444 1932. Plain Dead Soft Copper Strip, Bars and Rods, for the Windings of Electrical Machines.
- 659 1936. Light Gauge Copper Tubes.
- 672 - 1936. Hard Drawn Copper-cadmium Solid and Stranded Circular Conductors for Overhead Power Transmission.
- 699 1936. Copper Cylinders for Domestic Purposes.
- 711 713 1936. Cold Rolled Brass Sheets, Strip and Foil. (Copper, 80, 85 and 90 per cent.) (Up to and including 2 S.W.G. thickness.)
- 837 1939. Steel Cored Copper Conductors for Overhead Power Transmission Purposes.
- 264 1926. Hot Rolled Yellow Metal Plates, Sheet and Strip. (Excluding Condenser Plates and Ships' Sheathing.)
- 885 886 1910. Seamless Brass Tubes for General Purposes (Hard Drawn, 25 to 35 Tons per sq. in. Tensile and Annealed.)
- 897 -898 1916. Leaded Gun-metal Castings and Ingots. [Add. October, 1910.] [85 5 5 5.]
- 900 901 1910. Leaded Gun-metal Castings and Ingots. [Add. October, 1910.] [87 9 3 1.]
- 899 - 1910. Cold Rolled Copper Sheets and Strip (Half-hard and Annealed) for General Purposes (up to 3 S.W.G.).
- 920--1910. Naval Brass Die Castings.
- 932--1910. Brass Gravity Die Castings.
- 944 1911. Cast Brass Bars (suitable for Forging) and Forgings.
- 960 965 1911. Leaded Bronze Ingots and Castings (from 70 0 0/15 to 85 10 0 5).

IV. MISCELLANEOUS

- 206 --1924. Silver Solder.
- 219--1932. Soft Solders (Grades A, B, C, D, E, F, G, H, J and K).
- 220 -1926. Fine Zinc (or Spelter) (Grades A and B).
- 221--1926. Special Zinc (or Spelter).
- 222 - 1926. Foundry Zinc (or Spelter).
- 263--1931. Brazing Solders (Grades AA, A and B).
- 141 -1932. Cored Solder, Rosin Filled.
- 374--1930. Nickel-copper (Cupro-nickel) Sheets and Strip.
- 375- 1930. Refined Nickel (Grade A).
- 790--1938. Nickel Silver Sheets and Strip of 10 to 30 per cent Nickel Content (up to and including 3 S.W.G.).
- 801--1938. Lead and Lead Alloys for Cable Sheathing.
- 871--1939. Abrasive Papers and Cloths for General Purposes.

- 872—1939. Abrasive Papers and Cloths (Technical Products).
771—1938. Synthetic Resin (Phenolic) Moulding Materials and Mouldings.
668—1936. Laminated Synthetic Resin Bonded Sheet (Fabric Base) for Use as Gear Material.
474—1932. Synthetic Resins (Phenol-aldehyde Type) for the Manufacture of Boards, Tubes and Cylinders.
488—1923. Moulded Insulating Materials suitable for Accessories for General Electric Installations.
547—1934. Synthetic Resin Bonded-paper Sheets (Grade 1) for Electrical Purposes.
316—1929. Synthetic Resin Varnish Paper Boards and Tubes for General Electrical Purposes.
972—1941. Synthetic Resin Bonded Fabric Sheet for Electrical and Mechanical Purposes. (New Standard, September, 1941.)
626—1935. Micanite for Commutator Separators.
231—1936. Pressboard for Electrical Purposes. [Excluding "Built-up" Pressboard.]
234—1933. Ebonite for Electrical Purposes.
857—1939. Safety Glass for Land Transport.
934—1940. Vulcanized Fibre (Natural Colour) Rods and Tubes for Electrical Purposes.
1003, 1004—1942. High Purity Zinc and Zinc Alloys for Die Casting.
1007—1942. Summary of British and American Specifications for Non-Ferrous Materials.

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